Using SPI to Improve Print Yields

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Agenda

- How SPI is typically used in production
- Case studies of how it has been used to test
  - Stencils
  - Vendors
  - Foil Materials
  - Foil Coatings
  - Solder Pastes
  - Wipe Frequency
  - Tooling
- Summary on testing
- New, automated SPI capabilities
- Questions
Process Improvement with SPI

• Traditionally used on assembly lines to boost first-pass yields by identifying/eliminating print defects
  – Not a substitute for good process engineering or an excuse to ignore design issues!

• Use SPI tools to improve overall printing process
  – Small experiments that can be done during production or during breaks/changeovers to prevent print defects
  – Covers stencils, pastes, tooling, overall process
Automated SPI

- Uses white light and/or laser light
- Most often used on assembly line, right after the stencil printer
  - Detects solder deposits that may cause process defects: shorts, opens, insufficients, solder balls
  - Prevents soldering defects by identifying print defects before they go any further down the line
- Collects volume, position and height data on each print deposit
  - Pass or fail determined by comparing readings to user-programmed thresholds
Instant Feedback

- Process changes **quantified immediately**
  - Not qualified by visual inspection under microscope
  - Not quantified hours or days later by first pass yields
- Understand how changes in print parameters affect the output
  - Separation speed
  - Print speed
  - Print pressure
- Makes dialing in the process faster and easier
- Makes responding to changes in inputs (boards, stencils, pastes) faster and easier
How SPI Improves Yields

- Prevents print defects from becoming end-of-line defects
- SPC warns if process is heading out of control
- Helps identify problem areas
  - Component specific (package type)
  - Location specific (tooling)
- All improvements based on print defect history

First you have to make the defects before you can eliminate them
Proactive Yield Improvement

• Use SPI to strengthen the inputs to the system:
  • Stencils
  • Paste
  • Tooling
  • Cleaning
  • Coating
• More consistent inputs make for more consistent outputs
• Improves overall process quality
Running Experiments

• Everybody loves a giant, full factorial DOE that nails down main effects of multiple variables and all their \( n^{\text{th}} \) order interactions.
• But they are expensive, complicated and time consuming
• You can wait weeks, months or years for results
• In production, you need instant improvements

Small DOEs bring incremental process improvements quickly and easily
Little Experiments

- Don’t take the assembly line down
  - Run with small tweaks as part of production
  - Run during production breaks or changeovers

- Keep it simple

- Bring instant improvement to yields
10 Print Test

- A nice, quick test that usually generates enough data to provide a statistically significant sample size
- **Can often be run with production**, depending on the test
- Requires 10 bare PWBs and maybe one or two dummy PWBs
  - If you use dummies, cover them with clear plastic to make cleaning between prints easier
  - Plastic is sold as “self-laminating sheets” from the office supply store
10 Print Test

1) Set up the printer & SPI
   - If using new paste or if printing was paused, knead at least 10 times
2) Wipe the stencil before each test print
   - Unless you are testing wipe frequency 😊
3) Pick a squeegee stroke to measure – front to back or back to front (optional)
   - Run the dummy board or a production board to return the print head to its starting position
   - Wipe after return
4) Export the data to Excel
Managing the data

• **Maintain integrity of original data**
  – Save Excel file with word “original” in the filename
  – Do a Save As with “modified” in the filename, so if your computer chokes, you can still revert back to original data

• **Hide or Delete all the columns you don’t need**
  – Time, Date, Pin Number, Bar Code, Height, etc.

• **Use filters or pivot tables to extract the good stuff**
  – Volumes, sorted by input variables like aperture size or component type
  – Positional offsets

*Tip: Make sure to save the original data and work with the new file in case your computer hiccups.*
Data Calculations

• Average (mean) volume

• Coefficient of Variation
  – Standard Deviation as a % of mean
  – Good way to compare data sets
  – Should be <10%, 15% max

• Transfer Efficiency: average paste volume divided by aperture volume, %
  – Depends on area ratio of stencil aperture
  – Good way to compare different data sets

• Cpk: minimum of
  – (Avg - LCL)/3*StdDev or (UCL – Avg)/3*StdDev
  – Requires similar control limits for good comparison
Stencil Tests

• Vendor Qualification
  – Which vendor’s stencils provide the best paste release?
  – Which vendor’s stencils provide the best positional accuracy?
  – Which vendor’s stencils provide the most repeatable paste release?

• Stencil Verification
  – Apertures right size and location?

• Material or Manufacturing Process
  – Electroformed, laser cut, E-form L-cut, electro polished?
  – Nano-coating, OEM or aftermarket?
## Stencil Supplier Qualification

<table>
<thead>
<tr>
<th>Vendor Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1)</strong> Make short list of potential suppliers &amp; order test pieces</td>
</tr>
<tr>
<td>- based on technical capability, response time, cost, etc</td>
</tr>
<tr>
<td><strong>2)</strong> Do the 10 Print Test</td>
</tr>
<tr>
<td><strong>3)</strong> Select components to analyze print quality</td>
</tr>
<tr>
<td><strong>4)</strong> Examine Data for:</td>
</tr>
<tr>
<td>- Transfer efficiency</td>
</tr>
<tr>
<td>- Volume repeatability – Standard deviation as % of mean (or Cpk)</td>
</tr>
<tr>
<td>- Positional accuracy – average offset in X and Y</td>
</tr>
<tr>
<td>- Print Yield</td>
</tr>
<tr>
<td>- Total number of defects</td>
</tr>
</tbody>
</table>
## Results of A Supplier Evaluation

<table>
<thead>
<tr>
<th>Supplier</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td># Bds passed</td>
<td>10</td>
<td>5</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td># Bds failed</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Avg # of defects/ bd*</td>
<td>0</td>
<td>1.5</td>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>Cpk - uBGA</td>
<td>1.74</td>
<td>1.56</td>
<td>1.65</td>
<td>1.69</td>
</tr>
<tr>
<td>Cpk - 0201</td>
<td>3.4</td>
<td>2.74</td>
<td>3.17</td>
<td>3.43</td>
</tr>
</tbody>
</table>

* on boards containing defects

**#1**

**#2**
Why did Supplier C Fail Every Print?

This is also why you should verify your stencil before putting it into production.
Verifying Stencils Prior to Production

• Used to be common practice
• Not often performed any more
  – Many more apertures
  – Apertures are smaller
  – Visual assessment not good enough
• Automated measurements to check stencils at vendor’s facility
  – “Certified Vendor”
  – Can be a risky practice
• Stencil verification with SPI only takes 10 minutes
Verifying Stencils

<table>
<thead>
<tr>
<th>Stencil Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Print 2 boards, run thru SPI</td>
</tr>
<tr>
<td>- If they pass, export the data for review</td>
</tr>
<tr>
<td>2) If one or both fail, inspect the stencil for visible damage</td>
</tr>
<tr>
<td>- If damage is found, set aside for engineering review</td>
</tr>
<tr>
<td>- If no damage is found, run 2 more prints</td>
</tr>
<tr>
<td>3) If both prints pass, export the data for review</td>
</tr>
<tr>
<td>- If either fails, set aside for engineering review</td>
</tr>
<tr>
<td>4) Analyze data for selected component types</td>
</tr>
<tr>
<td>- If minimum Cpk &gt; 1.33 is met, approve stencil for production</td>
</tr>
</tbody>
</table>
Verification Process

1. Setup Printer and SPI machine
2. Print 2 boards
3. Inspect
   - Pass?
     - Y: Export data and calculate Cpks
       - N: Obvious stencil defect?
         - Y: Return to supplier
         - N: Hold for review
     - N: nbr 2nd fail
       - Y: Qualify for Production
6. 1st fail
   - Y: Return to supplier
   - N: Nbr 1st fail
     - Y: Obvious stencil defect?
       - Y: Return to supplier
       - N: Hold for review
     - N: Cpk > 1.33?
       - Y: Qualify for Production
       - N: nbr 2nd fail
         - Y: Qualify for Production
         - N: Hold for review

Testing Stencil Foil Materials

Material Evaluation

1) Select materials
2) Isolate material as variable
   - Cut under similar conditions
   - Print under similar conditions
3) Do the 10 Print Test
4) Calculate means and std deviations of volumes
5) Measure Apertures (optional)
6) Calculate Area Ratios (AR) and Transfer Efficiencies (TE)
   - AR = Ap size / 4x thickness
   - TE = Avg vol/aperture vol
7) Plot TE vs AR
8) Review std dev as % of mean
   <10 - 15% is target
   Relative comparison
Foil Materials’ Effect on Release

Fine grain (FG) and electropolished (EP) stencils outperformed laser nickel and standard stainless steel.
Foil Materials’ Effect on Release

Fine grain (FG) and electropolished (EP) stencils outperformed laser nickel and standard stainless steel for all pad configurations.
Stencil Coatings

- New option in stencils
- “Nano” coatings repel flux
  - “Fluxophobic, Hydrophobic, Oleophobic”
  - Make the paste want to stick to the PWB more than to the stencil
- Can be applied by vendor or assembler
- Coats bottom surface and/or inside of aperture walls
- Many unknowns still abound...
  - Durability, cleanability, potential joint contamination
## Testing Stencil Coatings

<table>
<thead>
<tr>
<th>Stencil Coating Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Order stencils in pairs</td>
</tr>
<tr>
<td>2) Apply coating to one</td>
</tr>
<tr>
<td>3) Do a 10 print test with each stencil</td>
</tr>
<tr>
<td>4) Export the data and compare</td>
</tr>
<tr>
<td>- Volumes, Repeatability Yields</td>
</tr>
<tr>
<td>5) Test also included foil materials, thicknesses and suppliers</td>
</tr>
</tbody>
</table>
Did The Coating Improve Anything?

- Print Yields improved in nearly all cases
- 7 of the coated produced 100% yields
- 1 of the uncoated produced 100% yield

- Of the 13 pairs of stencils tested:
  - TE decreased for BGAs; stayed the same for 0201s
  - Cpks did not improve

<table>
<thead>
<tr>
<th>Stencil</th>
<th>Stencil No.</th>
<th>Component</th>
<th>Actual AR</th>
<th>Actual TE</th>
<th>BGA Cpk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>0.58</td>
<td>0.60</td>
<td>0.46</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>0.70</td>
<td>0.71</td>
<td>0.54</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>0.55</td>
<td>0.66</td>
<td>0.45</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>0.67</td>
<td>0.78</td>
<td>0.54</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>0.121%</td>
<td>0.95%</td>
<td>0.91%</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>0.90%</td>
<td>0.81%</td>
<td>0.91%</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>113%</td>
<td>109%</td>
<td>109%</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>3.85</td>
<td>3.63</td>
<td>1.94</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>2.55</td>
<td>2.24</td>
<td>1.71</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>2.37</td>
<td>2.18</td>
<td>1.88</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>80</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>100</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>100</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>1 - B coated</td>
<td>1 - B not coated</td>
<td>0201</td>
<td>100</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

- E-form
- Laser Ni
- SS

| 2 - B coated | 2 - B not coated | 0201 | 0.58 | 0.55 | 0.65 |
| 2 - B coated | 2 - B not coated | 0201 | 0.65 | 0.55 | 0.64 |
| 2 - B coated | 2 - B not coated | 0201 | 0.66 | 0.55 | 0.64 |
| 2 - B coated | 2 - B not coated | 0201 | 0.68 | 0.55 | 0.64 |
| 2 - B coated | 2 - B not coated | 0201 | 0.75 | 0.55 | 0.64 |
| 2 - B coated | 2 - B not coated | 0201 | 0.81 | 0.55 | 0.64 |
| 2 - B coated | 2 - B not coated | 0201 | 2.94 | 3.34 | 3.25 |
| 2 - B coated | 2 - B not coated | 0201 | 2.24 | 2.18 | 2.3 |
| 2 - B coated | 2 - B not coated | 0201 | 1.7 | 2.18 | 2.3 |
| 2 - B coated | 2 - B not coated | 0201 | 80 | 80 | 40 |
| 2 - B coated | 2 - B not coated | 0201 | 100 | 30 | 40 |
| 2 - B coated | 2 - B not coated | 0201 | 100 | 30 | 40 |
| 2 - B coated | 2 - B not coated | 0201 | 100 | 30 | 40 |

| 3 - A coated | 3 - A not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 3 - A coated | 3 - A not coated | 0201 | 0.78 | 0.66 | 0.77 |
| 3 - A coated | 3 - A not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 3 - A coated | 3 - A not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 3 - A coated | 3 - A not coated | 0201 | 0.78 | 0.66 | 0.77 |
| 3 - A coated | 3 - A not coated | 0201 | 81% | 87% | 87% |
| 3 - A coated | 3 - A not coated | 0201 | 10% | 106% | 106% |
| 3 - A coated | 3 - A not coated | 0201 | 3.01 | 3.15 | 2.97 |
| 3 - A coated | 3 - A not coated | 0201 | 2.03 | 2.13 | 1.76 |
| 3 - A coated | 3 - A not coated | 0201 | 100 | 100 | 100 |
| 3 - A coated | 3 - A not coated | 0201 | 100 | 30 | 100 |
| 3 - A coated | 3 - A not coated | 0201 | 100 | 30 | 100 |
| 3 - A coated | 3 - A not coated | 0201 | 100 | 30 | 100 |

| 4 - A coated | 4 - A not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 4 - A coated | 4 - A not coated | 0201 | 0.77 | 0.66 | 0.77 |
| 4 - A coated | 4 - A not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 4 - A coated | 4 - A not coated | 0201 | 0.77 | 0.66 | 0.77 |
| 4 - A coated | 4 - A not coated | 0201 | 0.76 | 0.66 | 0.77 |
| 4 - A coated | 4 - A not coated | 0201 | 106% | 106% | 106% |
| 4 - A coated | 4 - A not coated | 0201 | 87% | 87% | 87% |
| 4 - A coated | 4 - A not coated | 0201 | 3.21 | 3.21 | 3.44 |
| 4 - A coated | 4 - A not coated | 0201 | 2.04 | 2.04 | 2.06 |
| 4 - A coated | 4 - A not coated | 0201 | 2.3 | 2.3 | 2.3 |
| 4 - A coated | 4 - A not coated | 0201 | 100 | 80 | 100 |
| 4 - A coated | 4 - A not coated | 0201 | 100 | 80 | 100 |
| 4 - A coated | 4 - A not coated | 0201 | 100 | 80 | 100 |

| 5 - D coated | 5 - D not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 5 - D coated | 5 - D not coated | 0201 | 0.77 | 0.66 | 0.77 |
| 5 - D coated | 5 - D not coated | 0201 | 0.66 | 0.66 | 0.66 |
| 5 - D coated | 5 - D not coated | 0201 | 0.77 | 0.66 | 0.77 |
| 5 - D coated | 5 - D not coated | 0201 | 0.76 | 0.66 | 0.77 |
| 5 - D coated | 5 - D not coated | 0201 | 106% | 106% | 106% |
| 5 - D coated | 5 - D not coated | 0201 | 87% | 87% | 87% |
| 5 - D coated | 5 - D not coated | 0201 | 3.21 | 3.21 | 3.44 |
| 5 - D coated | 5 - D not coated | 0201 | 2.04 | 2.04 | 2.06 |
| 5 - D coated | 5 - D not coated | 0201 | 2.3 | 2.3 | 2.3 |
| 5 - D coated | 5 - D not coated | 0201 | 100 | 80 | 100 |
| 5 - D coated | 5 - D not coated | 0201 | 100 | 80 | 100 |
| 5 - D coated | 5 - D not coated | 0201 | 100 | 80 | 100 |
Coating’s Effect on Print Yields

Coating improved print yield in all but the absolute worst cases (1C & 1D)
Effects of Coating

- Dramatically improved yields
- Did not impact repeatability
- Lowered transfer efficiency at AR ~0.66
- Comparable transfer efficiency at AR ~0.77
- Made bad stencils perform better
  - *Is this a good thing or a bad thing?*
Effects of Material, Mfg Process and Foil Thickness

- SS had higher yields than Eform or Laser Ni
- SS more dimensionally stable than Eform or Laser Ni
  - Thickness, aperture size and position
  - Superior dimensional accuracy, regardless of supplier
- SS had better overall volume repeatability
  - Process outputs very dependent on dimensional stability
- No alloy was a clear winner in SS category
- SS produced higher average volumes, even with thinner foils
  - For BGAs, 4mil foils deposited an average of 322 mil$^3$ of solder paste; 4.5mil laser Ni deposited an average of 250mil$^3$ (theoretical is 366 mil$^3$)
Solder Paste Tests

- Release characteristics
- Powder size
- Flux formulation – stencil life, print speed, environmental resistance, response to pause...
- Operating temperature window
Effect of Solder Powder Size

- When to move from Type 3 to Type 4 or 5?
- What does it get you?
Powder Size

Powder Size Test

1) Get solder pastes with same flux and different powders.
2) Do a 10 print test with each solder paste
3) Select the component types you want to analyze for
4) Export the data and compare
   - Mean
   - Std Dev as % of mean
   - Cpk
5) Reflow the samples. Look for:
   - Solder balls
   - Poor coalescence
   - Graping
   - Voiding, esp on QFNs
Type 3 vs Type 4 Powder

Type 4 gives slightly better release

Type 4 gives less variation at ARs below 0.6 but >20% is unacceptable, anyway
Type 3 vs Type 4 Powder

- Improvements in release and repeatability are marginal
- Type 4 known to present more reflow issues:
  - Solder balling, poor coalescence, “graping,” voiding under QFNs
  - Due to increased specific surface (ratio of surface area to volume) of smaller spheres and oxides on the sphere surfaces
- Newer technologies (fine grain SS, stencil coatings, optimized powder) enable pushing 0.66 area ratio with Type 3 powders
- Type 5 gives better print results but requires N₂ in reflow
Cleaning

- Papers
- Solvents
- Wipe Frequency
  - Test replaces visual assessment through microscope
  - Way faster and more accurate
## Wipe Frequency Test

1. Can be run during production
2. Do a 10 print test, using both squeegee directions, without wiping between prints
3. Record the print number where board was failed
4. Wipe stencil
5. Repeat three times
6. Determine lowest number of print when defects occur
7. Set the wipe frequency at least one less than the number of prints where the defects occurred.
Tooling

• **10 Print Test**
  – Custom vs Universal board supports
  – Pin support locations

• **Data Mining**
  – Effect of edge clamping
  – Find weak spots in support
Data Mining

1) Download SPI production data to Excel
2) Sort by assembly number to ID assy with most print defects
3) Take data for biggest hitter and sort by defect type and component type
   - Defect type dominance indicates systemic problem
4) If component type is dominant, drill deeper
   - Reference designators
   - Pin numbers
Data Mining

• Defect mode dominance indicates systemic problem
  – Board support, PCB pad sizes, mask registration, stencil aperture sizes or locations

• Component type dominance requires a closer look:
  – Reference designator – defects clustered in a certain area indicate a tooling problem – board support, edge clamp or stencil
  – Reference designator – if defects are on a single component, drill down to pin numbers and check apertures
  – Reference designator – if defects are spread about the board, check pad and aperture sizes
Data Mining

![Bar chart for Solder Paste Inspection Yields]

- Assembly Part Number ID:
  - A: 61
  - B: 41
  - C: 35
  - D: 60
  - E: 95
  - F: 5
  - G: 23

- Number of Panels:
  - A: 429
  - B: 298
  - C: 237
  - D: 134
  - E: 95
  - F: 5
  - G: 23

![Bar chart for Defect Type]

- Quantity:
  - Solder Bridge: 59
  - Excessive Volume: 1554
  - Insufficient Volume: 3202
  - Positional Error: 2194

![Bar chart for Components with Insufficient Paste Volumes]

- Component Type:
  - Component 59: BGA36 (5mm)
  - Component 1554: Other
  - Component 3202: Other
  - Component 2194: Other

Assy E -> Insufficients
BGA36 (.5mm)
Summary

• SPI is a good tool to for improving first pass yields
  – It catches print defects before they become soldering defects
  – Traditional applications require defects to first be created before they are eliminated

• Using SPI technology to prevent defects adds additional value
  – No cleaning or scrapping of bad prints
  – Overall tighter process
  – Proactive vs reactive
Summary - Tools

• 10 Print Test
• SPI database
• Excel

• Calculate and Compare:
  – Mean Volumes
  – Transfer efficiencies
  – Standard Deviations as % of Mean Volumes
  – Cpk values (if control limits are similar)
Investigations

• Stencils
  – Supplier qualification, verification for production, effect of foil material, effect of coating

• Solder paste
  – Effect of powder size

• Production Parameters
  – Wipe frequency

• Data Mining
  – Identify systemic and/or localized issues
New Software Apps

• Use the data the SPI generated during inspection to:
  – Feedback positional offsets to printer
  – Trigger an automatic stencil under wipe
  – Feed positional offsets forward to the placer
  – Integrate data with AOI to spot trends and drive SPI tolerances

Software automates tasks that humans could do, and does them consistently
More New Software Apps

Computer-generated images of measured solder paste deposits
Next Generation SPI

• Will improve reference plane determination
  – Current technology measures everything from 1-2mils above the pad to eliminate noise from PCB topography
  – Sufficient for prints 4mils or higher, but not for smaller deposits

• Will combine 2-D and 3-D (light and laser) in a single sensor to incorporate the advantages of each into measurement system

LGAs and 0.3mm BGAs/CSPs will drive the adoption of new measurement technology
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Thank You!

Questions?

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