As originally published in the IPC APEX EXPO Conference Proceedings.

Enabling High-Speed Printing Using Low Cost Materials: Process Stability is Paramount

Michael J. Cieslinski, Brent A. Fischthal

Panasonic Factory Solutions Company of America

Abstract

The rapid growth of electronic devices across the globe is driving manufacturers to enhance high-speed mass production techniques in the printed circuit board assembly arena. As manufacturers drive to reduce costs while maximizing production by expanding facilities, updating automation equipment, or implementing lean six sigma techniques, the potential to build scrap product or rework printed circuit boards increases dramatically.

Manufacturers have two general paths to reduce the costs of high-speed printed circuit board assembly production. The first path is to reduce cost by focusing on high quality printing and mounting. The other, increasingly popular option is to utilize low-cost materials. In either case, the baseline must provide a consistent high-speed solder paste printing method, which considers the fill, snap-off, and cleaning processes.

Building on our expertise and testing, this paper will highlight the two trains of thought with specific focus on how low-cost materials affect print performance. It will also explore technologies, which can help provide stable, high-speed screen-printing.

In the end, both paths aim to maximize profitability. As such, understanding how manufacturers can successfully integrate low-cost materials will help ensure high-quality production, reduce costs, and maximize profitability in a high-volume printed circuit board assembly environment.

Introduction

A fundamental way to improve the printing process is to develop a printing method, which considers possible manufacturing or process issues. In terms of print quality, the baseline should be a stable, consistent print process that generates the right shape, in the right location, using the right amount of solder. We can split the printing process into two processes: the fill, which inserts solder into the mask aperture, and the snap-off, which removes excess solder from the mask aperture. These two aspects combine for high-quality printing. Yet, the cleaning process is also an important factor in stabilizing print quality. Cleaning is not simply cleaning the mask; it is also critical to maintaining good printing quality. Cleaning performance relies on suction, which removes solder from the mask aperture, and underside cleaning, which wipes the underside of the mask. Maintaining print conditions requires a balance of suction and underside cleaning.

When developing a stable printing process, the fill, snap-off, and cleaning are critical. Nevertheless, inconsistencies in materials can be a significant cause of process fluctuations. While suppliers develop machines and methods to achieve high-quality printing, the material performance greatly influences the results. Figure 1 shows Print Quality Cause-and-Effect.

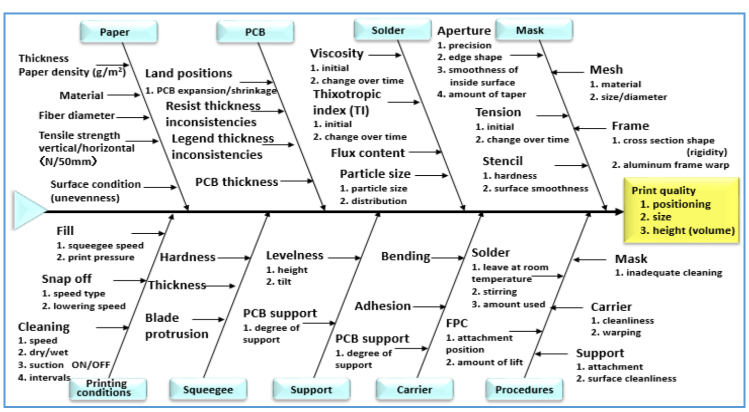

Figure 1 – Print Quality Cause-and- Effect Diagram

Managing the Print Process

Let us consider the specifics of what manufacturers need to manage in the printing process. Figure 1 outlines the factors manufactures need to consider. The main items involve materials, procedures, and machine conditions. The materials include masks, solder, PCBs, and paper. Jigs and tools include squeegees and support devices. Depending on the transfer method, carriers may also be a factor. The manufacturer must properly manage each of these aspects before creating an ideal condition.

For example with the mask, we recommend laying out specifications for aperture processing and mask tension, and then creating an inspection sheet to verify the materials meet said specifications. Additionally, we recommend creating specifications for the various mask components, such as the stencil, aluminum frame, and mesh material. It is important to devise quality specifications based on the previous cause-and-effect diagram and summarized in Figure 2.

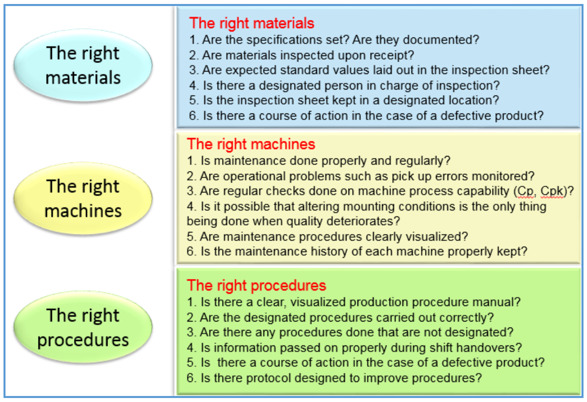

Figure 2 – Devising Quality Specifications Based on Cause-and- Effect Diagram in Figure 1

The manufacturer must implement guidelines to ensure operators complete the tasks. Yet, the tasks need to be minimal and simplistic to ensure compliance and completion by the operator. Most importantly, they must be effective and relevant to ensure enforcement on the production floor.

Production Mentality

When a manufacturing facility controls the "4 M's" on its manufacturing floor (Materials, Machines, Men, and Methods) good products should follow. Specifically, high-quality product will result if the machines are well maintained, the ideal methods are devised, the materials meet the specifications, and the men implement the proper procedures. Therefore, the goal of equipment manufacturers is to minimize the items managed in the production line and to develop equipment and methods supporting material performance inconsistencies. This focus is becoming more important as we consider the various trains of thought on production. One concept is to maximize cash flow through high-quality mounting; another concept growing in popularity aims to maximize cash flow by using low-cost materials.

Material Costs and Mounting Quality

Unsurprisingly, low-cost materials result in higher average defect rates compared to ideal materials. However, the biggest issue with using low-cost materials is the inconsistent defect rates, which makes the repair workload unpredictable and unstable. Our studies have shown the greatest reasons for this low-cost materials issue is the wide range of inconsistent initial performances and the significant performance degradation over time, as shown in Figure 3.

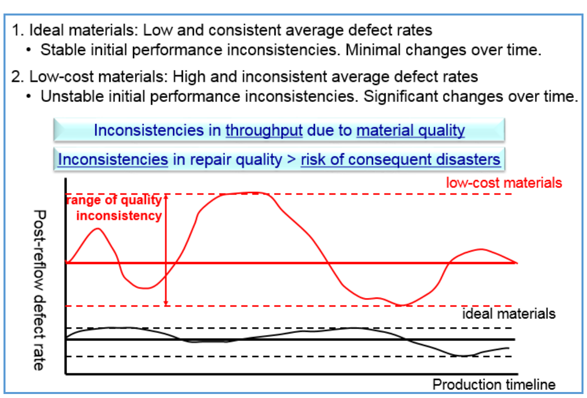

Figure 3 – The Relationship between Material Costs and Mounting Quality

To handle the increasing use of low-cost materials requires a screen printing method able to withstand the effects of the initial material performance inconsistencies and their changes in performance over time. The objective of a Stable High-Speed Screen Print Method is to stabilize print quality even when using low-cost materials. Inconsistencies in initial performance and its changes over time are unpredictable with low-cost materials, and different combinations of solder, masks, PCBs, and other factors further complicate inconsistencies. Therefore, to prevent defective printing, the system must monitor for inconsistencies in print quality to rectify any problems in a timely manner. The concept is to prevent defects from occurring at all and keep the process within specification as shown in figure 4.

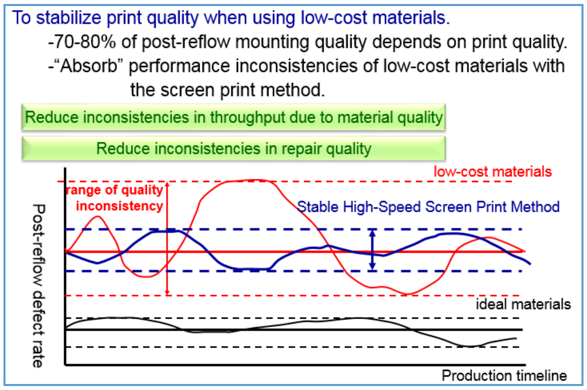

Figure 4 - Stable High-Speed Screen Print Method Objective

Performance Aspects of Low Cost Materials

The performance aspects of low-cost materials affect print quality. In the case of solder paste, its viscosity and thixotropic index greatly affects print quality. Inconsistencies in flux content also affect solder volume after reflow, causing inconsistencies in bonding strength. For masks, aperture processing conditions as well as frame rigidity and warp determine the initial mask performance. Like solder, the mask initial performance and degradation are large factors in stabilizing print quality. Unevenness on PCB surfaces as well as the performance quality of cleaning paper will also affect print quality. These inconsistencies in material performance aggravate inconsistent print results that result from print direction or the number of sheets printed. Now we will take a closer look at the material performances of solders, masks, and cleaning papers.

Solder Paste Performance Comparison

Our studies compared the physical properties of an ideal solder material against a low-cost solder material. The graphs in Figure 5 show the changes in viscosity and thixotropic index over time, measured at regular intervals over 48 hours using a production viscometer. As shown, the ideal solder changes slightly and its effect on print quality is minimal. However, low-cost solder changes significantly over time, and gets twice as viscous over the course of 48 hours. Many problems arise when the change is this significant. The most prominent problem is low solder amounts in the fill, a defect referred to as "open solder."

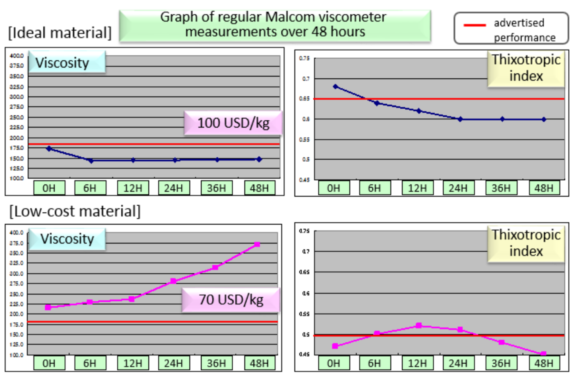

Figure 5 – Solder Paste Performance Results

Figure 6 shows examples of the paste consistency differences after 48 hours. The ideal solder, shown on the left, does not change as much over the 48 hours. However, the low-cost solder on the right appears dry and clumpy. Maintaining stable print quality with material in this state can be very difficult.

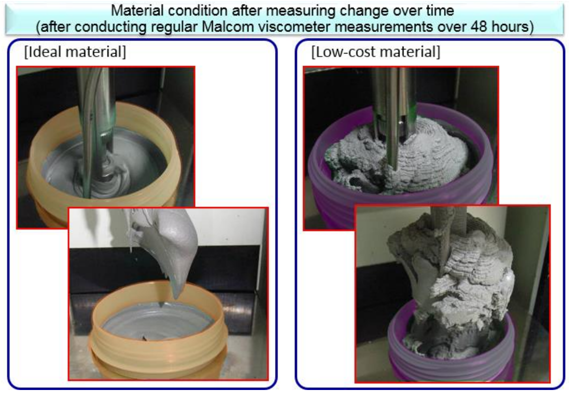

Figure 6 – Solder Paste Quality Comparison

As solder viscosity increases, the process issues begin to compound. Figure 7 shows a couple of actual customer problems occurring on the production floor when using low quality solder paste. The photo to the left shows an example of the squeegee picking up viscous solder. If printing continues without correction, there will not be enough solder to fill the apertures, resulting in an uneven print and lost yield. The right-hand photo depicts solder sticking to the squeegee. The printer is no longer applying solder onto the mask, so apertures will clearly lack sufficient solder, resulting in poor fill and yield.

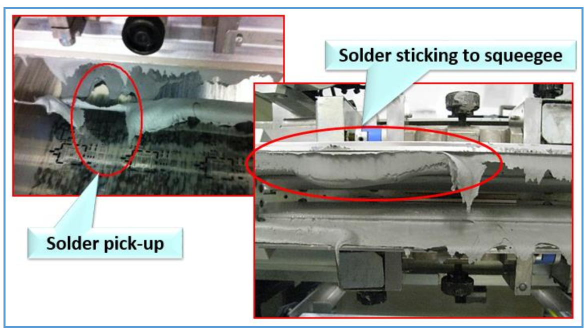

Figure 7 – Increased Viscosity Solder Paste Examples

An inline Solder Paste Inspection (SPI) or Automated Optical Inspection (AOI) machine could immediately detect any defects; otherwise, the defects may slip until post-reflow. In unfortunate cases, several dozen defects may occur before a manual inspection process locates them. In either case, the defect will negatively affect production quality.

Mask Performance Comparison

We will now move on to masks. Figure 8 shows two photos of different quality masks taken using an electron microscope at 200x (times) magnification. The difference in quality is obvious. The ideal mask material uses a process called electro-polishing after laser cutting to sharpen the aperture edges and smooth the inside walls of the aperture. However, low-cost mask materials are usually only laser cut, resulting in a very uneven surface, as shown in Figure 8.

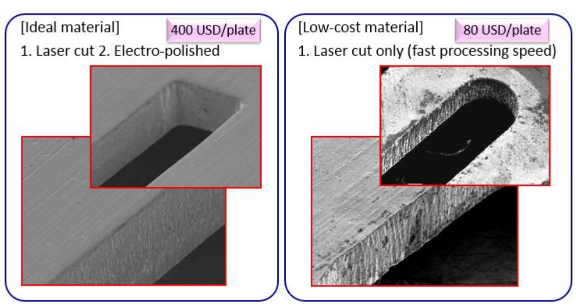

Figure 8 – Mask Aperture Condition Comparison

Mask Tension Comparison

The stronger and more even the mask tension, then the better the resulting print quality. The graph in Figure 9 shows tension measurements of masks used in a certain factory. We performed the measurements with a production tension-measuring gauge. As depicted in the data, the low-cost masks, on average, have weaker and less even tension. Our tests also measured new, unused low-cost masks that had just arrived at the factory. Although tension was strong in some places, it was not evenly distributed throughout the mask.

We also discovered that low-cost material tension dropped under the threshold value after about 20,000 prints. With tension this inconsistent, both bridging and open solder defects can result on the same PCB, and may not be resolved by merely changing printing conditions. In the worst-case scenario, tension inconsistencies combined with the solder's physical change over time may result in different types of defects appearing over the course of a single day.

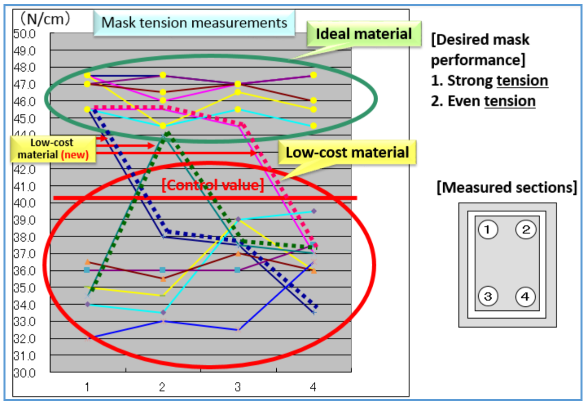

Figure 9 – Mask Tension Measurement Comparison and Test Points

A significant reason for low-cost masks to lose the tension is related directly to the quality of the mesh material comprising the screen. When a mask is manufactured, the mesh is typically attached to the aluminum frame with an adhesive. Then a laser-cut sheet of metal called the stencil is adhered on top. Finally, the supplier removes the excess mesh. The quality of the mesh material determines the mask tension degradation. Adhesive quality also serves as a factor.

The photos in Figure 10 shows two mesh types. The photo on the left shows #180 mesh, a common mesh size for ideal materials. The photo on the right shows #100 mesh, a common mesh size for low-cost materials. In general, the larger this number, the less change in tension over time. Our studies revealed the #100 loses tension twice as fast as the #180.

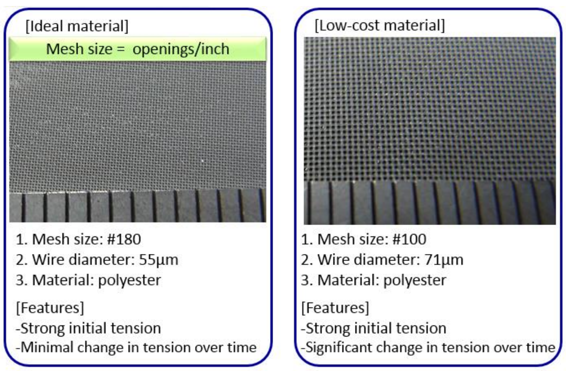

Figure 10 – Solder Mask Mesh Comparison

Mask Frame Comparison

Controlling the mask aperture processing and mask tension will help improve printing performance, yet defects and inconsistencies can continue. The mask frame must also be considered. In our studies, the masks producing good-quality prints were heavy, whereas, the masks producing poor-quality prints were lighter. Figure 11 shows a cross section of two sample frames. The cross section of the lighter mask aluminum frame is shown in the photo on the right. Through experimentation, we found that stretching mesh firmly over this less rigid frame caused the entire frame to warp.

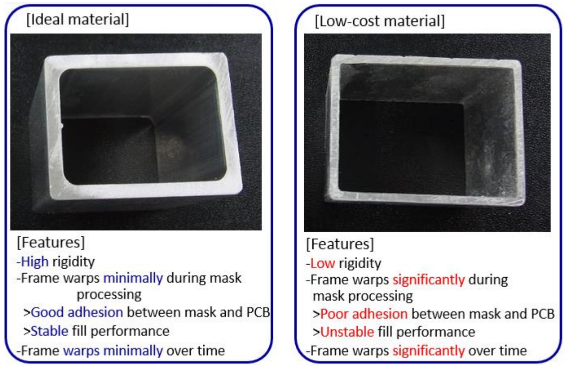

Figure 11 – Mask Frame Comparison

Cleaning Paper Comparison

Cleaning paper performance is also a significant factor in print quality. There are several important aspects of paper quality to consider, yet how well the paper wipes solder from the underside of the mask is what affects print quality the most. The photo on the left in Figure 12 shows ideal paper material. This paper has fine fibers that catch and retain solder well for a clean wipe.

Very little solder reattaches to the mask. The photo on the right shows low-cost paper, and the solder is not caught in the fibers, but merely smears onto the surface of the fibers. This does not stop the solder from reattaching to the mask. Linting is another problem with low-cost paper. The paper lint becomes caught on the edges of the mask apertures, causing the mask to clog and reducing print quality

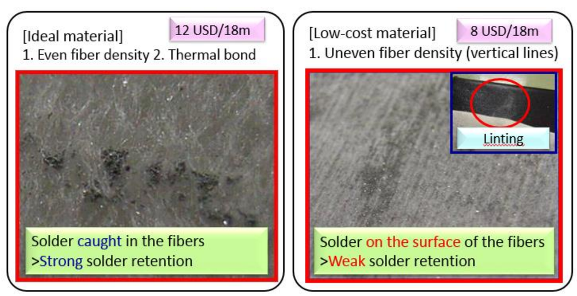

Figure 12 – Cleaning Paper Comparison

Cleaning Paper Performance

There is a significant a difference in solder wiping performance between papers. The photos in Figure 13 show cleaning paper examples at 200x magnification. The fibers in the ideal paper material intertwine in a complex, yet even manner. This wipes solder cleanly, and retains solder after wiping, preventing the solder from reattaching to the mask. However, fibers in the low-cost paper do not intertwine. They look like they have been pressed flat. This type does not retain solder well or prevent solder from reattaching to the mask. Linting is also an issue. A digital microscope was used to take these photos. Although low in precision, the microscope offers a measuring feature, and we were able to determine that the fiber diameter in this case was about 25 microns.

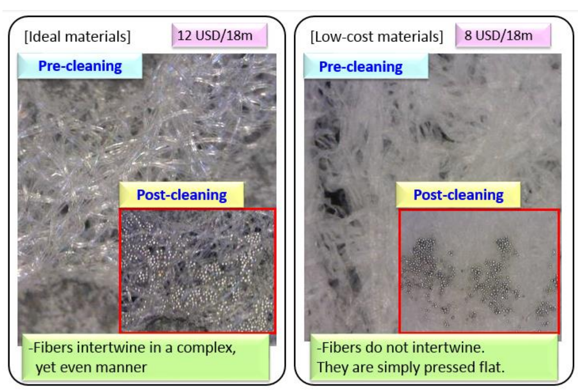

Figure 13 – Cleaning Paper Examples

Samples Results from Using Low-Cost Material
Low-cost materials like the mask and PCB can change the print quality, especially when considering the print direction. For example, out study simulated a situation whereby the top edge mask apertures are inconsistent, aperture wall surface is rough and inconsistent, the taper varies from side to side, the board resist and land positions are offset, and the printed silk height is inconsistent. Figure 14 depicts such a situation.

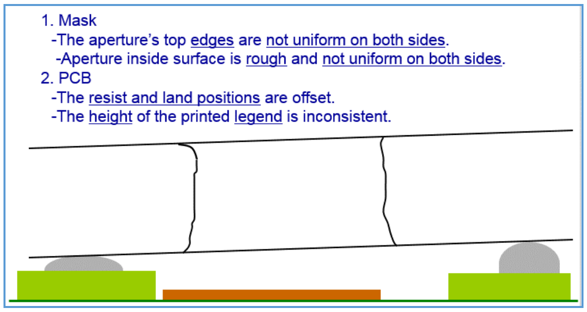

Figure 14 – Low Cost Material Situation Example

Figures 15 and 16 describe the solder fill results when printing in both directions and the changes occurring when the low coast materials are used

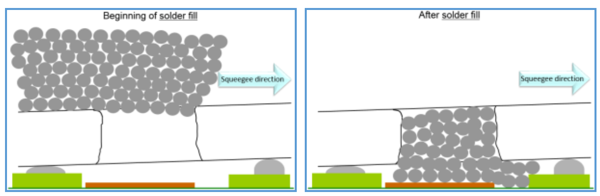

Figure 15 –Low Cost Material Results with a Left to Right Print Stroke

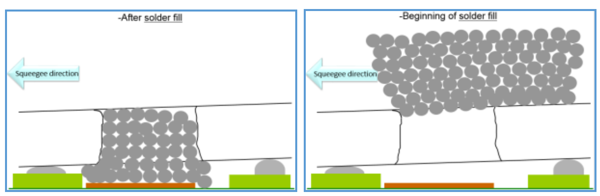

Figure 16 –Low Cost Materials Results with a Right to Left Print Stroke

There are clear differences in the fill depending on the print direction in this example using low cost materials. During snap-off, the printed solder further deforms due to the aperture surface conditions or the solder properties. If we add effects from mask tension to this mix, the resulting print deforms unpredictably.

Implementing Solutions to Enable Low-Cost Material Usage
The study recommends a combination of printing in both directions with a mask clean cycle after every print. This is an industry-accepted process to help mitigate material performance inconsistencies; however, it reduces tact times, which can significantly reduce throughput. The method also increases the use of cleaning paper, which increased operational costs.

During a study, the user implemented bi-direction printing and cleaning after every print cycle. Mount quality inconsistencies were reduced to about 60%. The average defect rate also went down 50%. In this case, our study classified the solder as an ideal material, but it defined both the mask and cleaning paper as low-cost materials.

Stable High-Speed Print Method Overview
Using low-cost materials is an enduring production consideration that suppliers and manufacturers alike must overcome to ensure the manufacturers achieve their production goals as expected. The stable high-speed print method encompasses the solder paste printer. The paper presents several recommended features to enable high-speed production with low-cost materials.

Double Blade Squeegee System When using a double-blade metal squeegee system, the printer increases fill ability even with low-cost masks or solders. In our experiments a double-blade system, as shown in Figure 17, has achieved proper fills at a squeegee speed of 400mm per second, while adapting to uneven PCB surfaces.

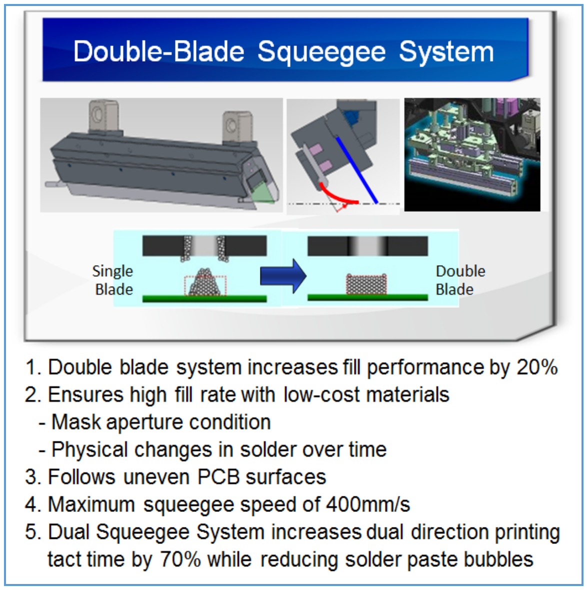

Figure 17 – Example of a Double-Blade Squeegee System

Mask Cleaning

The method involves wet cleaning that actively uses solvent, contrary to conventional cleaning protocols. Additionally, cleaning after every print keeps the mask underside clean even with low-cost cleaning paper. In past experiments, using wet cleaning excessively made flux adhere to the mask, causing clogging. When cleaning occurred once every 5 or 10 prints, a significant amount of flux would remain on the mask underside. Under such conditions, cleaning would often fail to remove that flux completely, and the residue would stick to the mask. This was especially a problem with low-cost papers.

However, the mask underside remains relatively clean when cleaning occurs after every print. Under these conditions, wet cleaning manages to wipe the flux off cleanly, and leaves no residue that can stick to the mask. Consequently, maintaining a clean mask underside is possible, even when using low-cost paper. Additionally, it reduces the amount of paper required for each cleaning to 12mm.

Maintaining vacuum on the mask during snap-off stabilizes the process even when the mask frame is warped or mask tension has decreased. Utilizing a vacuum hold as the mask is removed ensured stable snap-off even with changes in solder consistency or inconsistencies in mask aperture. Figures 18 and 19 highlight the cleaning and vacuum hold recommendations, respectively.

Figure 18 – Examples of Recommended Mask Cleaning Features

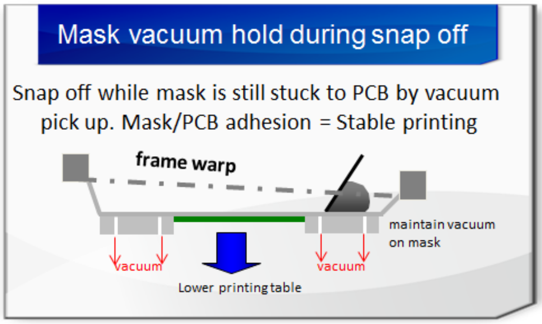

Figure 19 – Examples of Recommended Vacuum Hold Features

Results

Combining dual direction printing with cleaning after every print provides notable improvements. Figures 20-22 map the test run results and the resulting fill percentages. In conventional one-way printing (Figure 20), two peaks appear, one for each print direction, especially when using low-cost materials. Running back-and-forth prints under the same conditions consolidates the peaks into one (Figure 21), and the distribution of fill percentages shift slightly to the right. Cleaning after every print while printing in both directions narrows the distribution (Figure 22), and the frequency peak increases. The combination of the two succeeds in reducing inconsistencies in fill percentages.

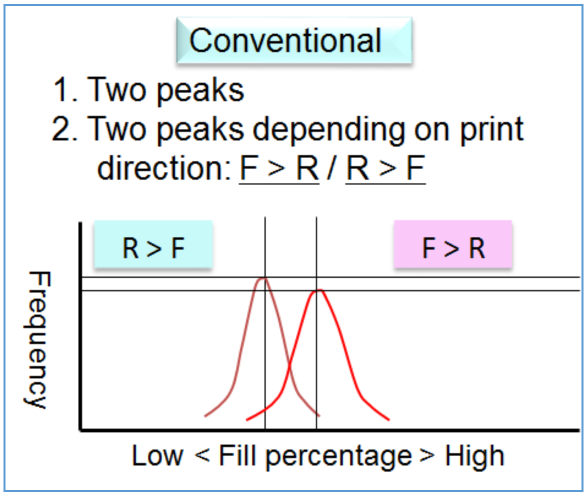

Figure 20 – Aperture fill percentage distribution, Conventional Method

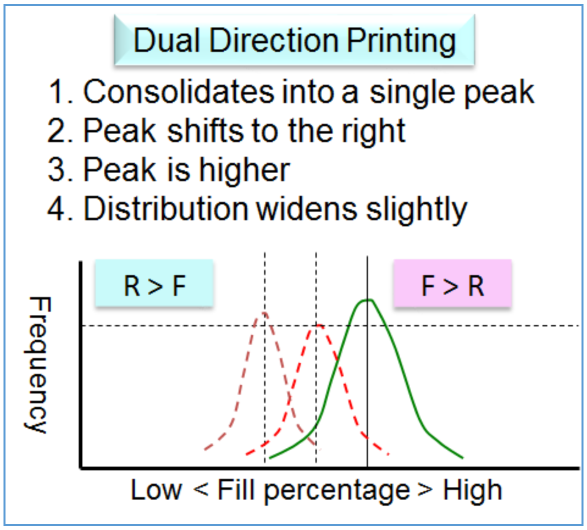

Figure 21 – Aperture fill percentage distribution, Dual Direction Method

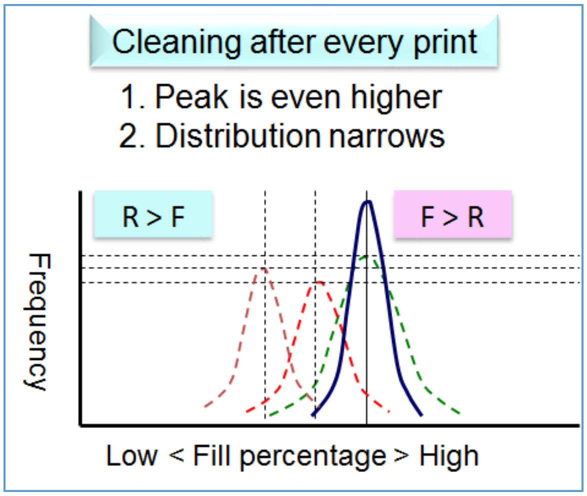

Figure 22 – Aperture fill percentage distribution, Cleaning Method

Solder Volume Comparison

Depending on the method, there are deviations when considering the total solder volume used for each PCB. Conventional one-way printing results are in Figure 23, where solder volume increases inconsistently with each print. The inconsistencies are due to changes in print direction. Dual direction printing under the same conditions (Figure 24) eliminates inconsistencies due to print direction, but quickly results in bridging defects. Yet, cleaning after every print in addition to dual direction printing (Figure 25) stabilizes solder volumes and minimizes those print direction inconsistencies. The study recommends using dual direction printing to stabilize print quality when using low-cost materials. Cleaning after every print is effective regardless of the materials.

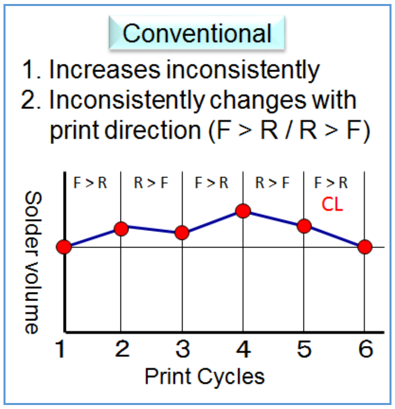

Figure 23 – Solder Volume per Board, Conventional Method

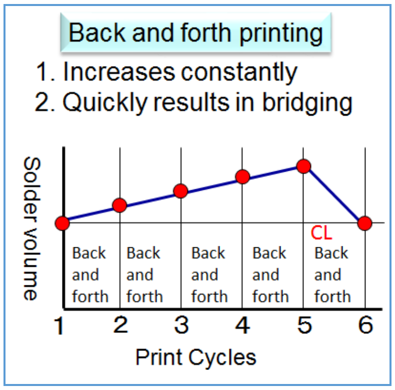

Figure 24 – Solder Volume per Board, Dual Direction Method

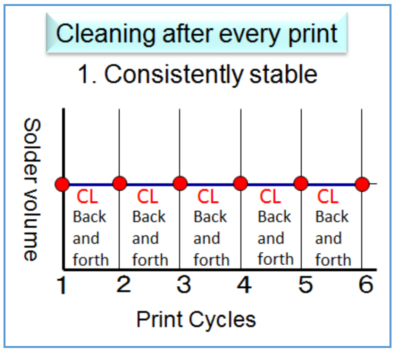

Figure 25 – Solder Volume per Board, Cleaning Method

Monitoring Solder Usage

Monitoring solder usage by using a line sensor can assist in automatically measuring the solder rolling diameters with high accuracy. The rolling diameter of solder changes slightly over the course of the fill. We have developed a way to measure accurate rolling diameters by experimenting with different methods and measurement intervals. Figure 26 shows the relationship between the actual amount of solder in the printing process and the solder rolling diameter.

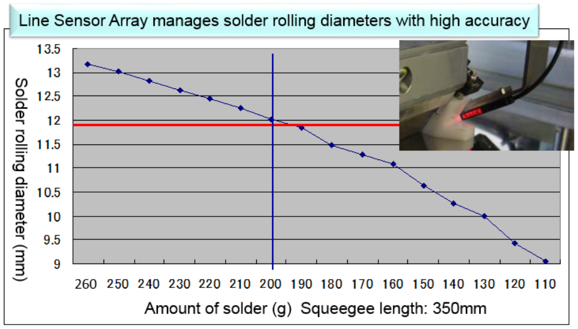

Figure 26 – Line Sensor Solder Usage Monitoring Example

Unlike conventional sensors, which detected the presence or absence of solder, a line sensor function allows accurate measurement and subsequent management of rolling diameters. Consequently, it is possible to limit fill inconsistencies stemming from changes in the rolling diameter to a minimum. It can also greatly reduce the amount of solder disposal during solder exchange compared to conventional methods where management was a visual estimation.

Conclusions

Our industry does not expect the forecasted use of low-cost materials like solders or masks to decline. Unfortunately, it is not possible for a single method to correct or mitigate all of the problems caused by low-cost materials. However, this study revealed several recommendations to help reduce current inconsistencies and increase mounting quality as much as possible. From our experience, reducing these inconsistencies will also help reduce defect rates; therefore, we will continue to explore the high-speed stable print method as it relates to reducing material-related inconsistencies. It is imperative capital equipment, consumables, and peripheral equipment providers' work together to provide a stable high-speed screen print method focused on using low-cost materials.