MOVING TOWARDS A STABLE PROCESS:

MINIMIZING VARIATION IN SOLDER PASTE PRINTING

George Babka
Assembléon America, Inc.
Alpharetta, Georgia, USA
george.babka@philips.com

Nobody likes change. In the world of process control, change is our enemy. Any change in a process known to work, incurs the unknown: the possible defect. In the world of solder paste printing much effort has been spent in finding what paste, stencil, print speed, print pressure, etc. works best for what we do.

We typically do not change print speed, squeegee print pressure, or solder paste type in the middle of a working process. We do not change these parameters because we know that they cause our process to become unstable and unpredictable.

One piece of the solder printing process that is constantly changing is the print pressure. Print Pressure is the amount of force the solder paste exerts during the filling of the aperture. Our measurements indicate that a change in the volume of solder paste on the stencil is one of the largest contributors to changing print pressure. The volume of solder paste can be stated as the diameter of the roll, or the weight of the total amount of paste on the stencil.

In most processes we print a certain number of boards and then dispense solder paste in a bead, or we have an operator manually apply paste onto the stencil. Either way, the amount of the paste on the stencil and therefore, print pressure can change quite dramatically through the course of a shift of production.

Dispensing small amounts of solder paste frequently in the center of the existing paste roll, allows the print pressure to remain virtually stable. This in turn removes a significant variable in the print process.

Key words: Print Process Control, Paste Dispense, Blade Angle, Squeegee Speed, Print Pressure, Process Stability

BACKGROUND

It has long been suspected that solder print definition and volume are affected by factors that are not readily changeable during the print process. Two of these factors are blade angle and solder paste volume on the stencil.

Blade Angle

Squeegee blade angle is the angle formed between the stencil and the squeegee at a zero pressure condition. This has generally been a function of the fixed angle of the squeegee holder, or the print head itself.

Some earlier stencil printer designs had the ability, within a narrow range, to mechanically change this angle during setup. This limited the operator to a single blade angle between changeovers.

As a result of this limitation and due to the fact that it was difficult to change, blade angle was typically set at one angle, and then was never changed again. Printer companies experimented with the idea of offering blades of different angles, but this never caught on in practice. For the most parts, each printer company settled on a single blade angle for their entire range of printers.

There is however, at least one machine that has challenged this convention, allowing for blade angle changes via a servo motor at any time in the printing process.

Volume of Solder on the Stencil

We know that the volume of solder paste placed on the stencil has an impact on overall solder paste print quality. For example, too much solder paste on the stencil will get caught up between the blades. This impedes the natural rolling action of the paste, resulting in insufficient paste depositions. The same result can be seen with too little solder paste: the small amount of material tends to slide across the stencil instead of rolling.

Efforts to minimize the potential for too much or too little solder paste on the stencil have focused mainly on the frequency and amount of solder paste dispensed via an automatic dispenser. Due to the time impact, these dispense cycles are typically programmed to be rather infrequent. The net effect is only to prevent either extreme: too much or too little solder paste on the stencil.

The introduction of enclosed print chambers ten years ago has largely minimized the effects of the amount of solder paste on the stencil for the machines that used them. However, these print heads have not been universally adopted as industry standards due to considerations such as cost, maintenance, ease of cleaning, and size variations of the substrate. Additionally, some older solder paste formulations as well as all water soluble pastes are not suited for this process.

PREVIOUS EXPERIMENTATION

Previously, the effects of blade angle and squeegee pressure have been explored as they relate to the effects on fine feature printing. In a study performed last year,[1] we determined that:

1. Greater solder paste transfer efficiency can be obtained for the same aperture size (area ratio) by reducing the blade contact angle.

2. Increasing Print Pressure may decrease the blade angle, but has a negative effect on transfer efficiency.

3. If blade angle is optimized, a lower area ratio can be used to print 01005's and Micro BGAs, allowing the opportunity to use a thicker stencil to print these fine feature devices.

TEST METHODOLOGY

Testing was performed at Yamaha's Hamamatsu, Japan laboratories. The goal of the testing was to determine the solder paste fill pressure changes, when modifying the following parameters.

1. Solder Paste Volume (100g – 500g)
2. Blade Angle (45 degrees – 65 degrees)
3. Squeegee Pressure (50N – 100N)
4. Squeegee Speed (30 mm/sec – 90 mm/sec)

Testing was done on a Yamaha YGP Printer with 350 mm long stainless steel blades. Blade Angle was modified via the use of a servo-controlled angle adjustment motor integrated into the machine's print head. Material used for the testing was an Alpha Metals, OM-325MS, SAC 305 Solder Paste.

For these experiments, a stainless steel stencil was used. A pressure transducer was mounted into the stencil to measure the downward paste pressure into the stencil. This was used to approximate the fill pressure of the paste into an aperture during normal printing operations. Diagrams of this can be seen in Figures #1 & 2, below)

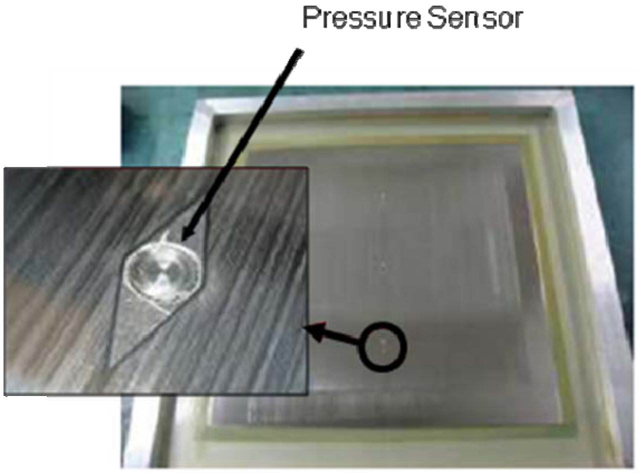

Figure 1. Pressure Sensor Location.

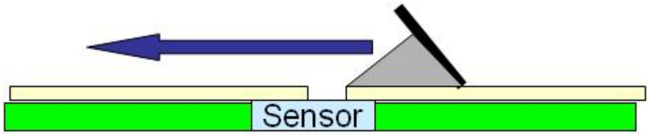

Figure 2. Sensor location relative to the squeegee stroke.

Only one parameter was changed at a time to determine their individual effects on pressure.

EXPERIMENT RESULTS

Solder Paste Volume

For the Paste Volume experiment, we used:

1. A blade angle of 55 degrees
2. A squeegee speed of 30 mm/sec
3. A squeegee pressure of 50 N
4. Paste volume was varied between 100 – 500 grams.

Pressure was measured throughout the print stroke and graphed as follows:

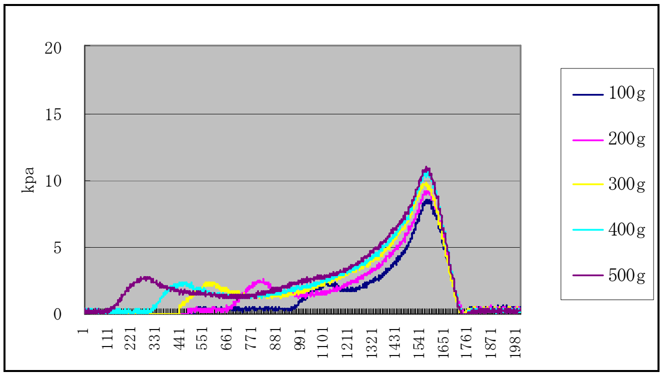

Figure 3. Pressure with Varying Paste Volumes.

Looking at the graph above, we can see several things:

General Observations

1. As the solder volume increases, there is a longer period of time that the transducer feels the pressure of the paste. This is expected due to the large diameter of the paste roll: the paste is over the transducer for a longer time.

2. As the solder initially contacts the paste sensor (Figure 4, Point A), there is a small spike in the pressure reading. Since the solder is rolling forward, we expect this, due to the downward force of the paste at the leading edge of the roll.

3. After the small spike, we see a drop in pressure, as the weight of the paste is transferred to the transducer (Figure 4, Point B).

4. As we near the point of contact of the squeegee with the stencil, we see the highest pressure (Figure 4, Point C). This is due to the shearing action of the paste at the blade tip. As the blade begins to pass the aperture, there is no place for

the paste to go but up the squeegee face. The filled stencil aperture provide the reaction force necessary to push the paste up the face of the blade.

5. It is important to note that the applied force on the squeegee blade is not the sole reason for the increase in pressure. If this were the case, we would not see the gradual buildup of the pressure to the peak. Rather, we would see a spike in pressure equal and opposite to the pressure drop at the end of the stroke. Furthermore, if the pressure spike was a result of the squeegee force, then we would see all of the peak pressures at the same value at the point of contact of the squeegee with the sensor.

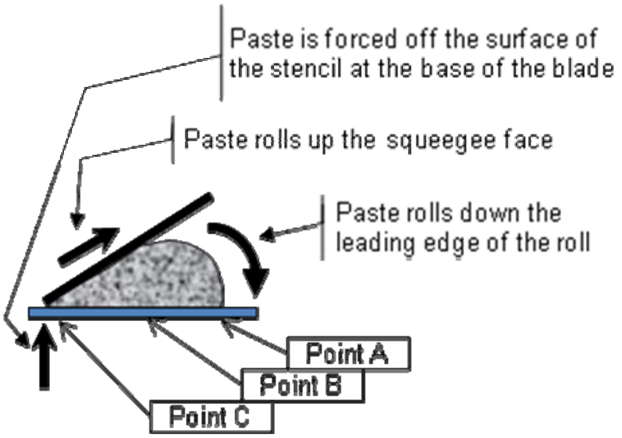

Figure 4. Paste Pressure at Different Points in the Print Stroke.

The above effects were common in all of the testing performed. In addition to this, we also saw a significant improvement in the paste pressure with a large diameter solder roll (Table 1).

Solder Paste Amount	Paste Roll Diameter	Max Pressure
100 g	10.4 mm	8.53 KPa
200 g	15.1 mm	9.23 KPa
300 g	17.5 mm	9.81 KPa
400 g	20.8 mm	10.66 KPa
500 g	23.3 mm	11.00 KPa

Table 1. Max Pressure for varying paste amounts.

In a majority of operations, we see operators scooping solder paste onto the stencil without really measuring the amount applied. To combat this, a few companies actually specify the amount of solder paste to be placed on the stencil at the beginning of a production run (i.e., one full 350 gram jar), but most do not.

Even these companies fall short of full control of the volume of solder paste on the stencil when setting up their paste dispenser. Most Paste dispense processes are suited to a larger volume of paste (75 – 150 grams), and dispensed at infrequent intervals (every 40 – 50 prints). As a result, the roll size can still change significantly during the course of a shift.

As seen from the above data, a 100g change in solder roll size will cause approximately a 7% change in maximum paste filling pressure. This is a significant change. It is enough to dramatically alter the solder paste print quality, especially on small apertures.

Attack Angle
For the attack angle experiment, we used:

1. A 300 g roll of solder paste
2. A squeegee speed of 30 mm/sec
3. A squeegee pressure of 50 N
4. Angle was varied from 45 – 65 degrees.

Pressure was measured throughout the print stroke and graphed as follows (Figure 5):

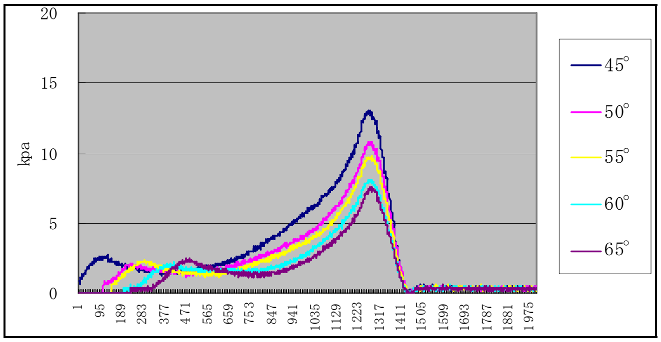

Figure 5. Pressure at Varying Blade Angles.

As we can see, similar characteristics are diplayed in this experiment. The lower squeegee angles flatten the solder paste roll. As a result, the same volume of solder paste contacts a larger area of the stencil (Figure 6). This causes the pressure to be felt over a longer period of the stencil stroke.

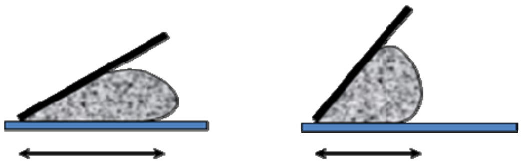

Figure 6. A Lower Angle Results in a Longer Contact Area for a Given Amount of Solder Paste.

Additionally, we see that the lower angles also result in a much larger maximum pressure. This makes sense, as the smaller volume at the tip of the blade should cause a larger force, as paste is pushed upwards along the face of the squeegee blade. The same amount of solder needs to travel through this smaller volume in the same amount of time, resulting in a higher paste flow rate for a lower angle.

The actual values can be seen Table 2, below:

Squeegee Angle	Max Pressure
45°	13.05 KPa
50°	10.86 KPa
55°	9.81 KPa
60°	8.18 KPa
65°	7.56 KPa

Table 2. Maximum Pressure at Various Blade Angles.

Squeegee Pressure

For the Squeegee Pressure experiment, we used:

1. A 300 g roll of solder paste
2. A squeegee speed of 30 mm/sec
3. An angle of 55 degrees
4. Pressure was varied between 50 and 100 Newtons.

Again, paste pressure was measured throughout the print stroke and graphed as follows (Figure 7):

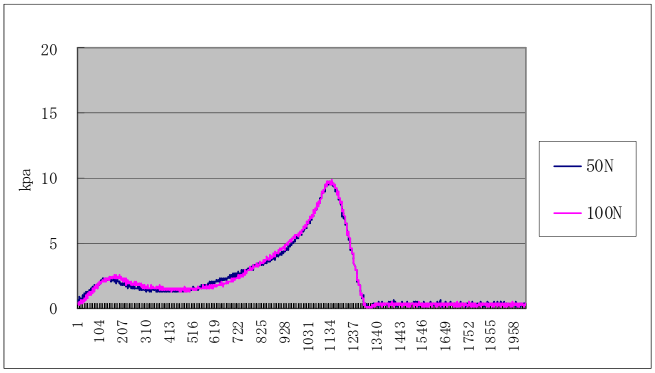

Figure 7. Pressure at Varying Squeegee Pressures.

The results of the two pressure conditions in this experiment proved to be almost identical. The actual values are shown below (Table 3):

Squeegee Force	Max Pressure
50 N	9.81 KPa
100 N	9.94 KPa

Table 3. Maximum Paste Pressure at Various Squeegee Pressures.

This is an interesting result, as it has previously been thought that a larger amount of squeegee force will bend the blade more, causing a higher filling force, as seen in experiment #2.

From this result, we can deduce that the angle changes that result from an increased print pressure are very small. If we were to calculate a hypothetical angle based on the pressure changes:

$$\Theta_{100N} = \Theta_{50N} - 5° \times \frac{(9.81 - 9.94)}{(9.81 - 10.86)}$$

We get a value of 54.38°, only a 0.62° change in angle for double the squeegee force.

It is standard industry practice to use only the minimum blade pressure necessary to wipe the surface of the stencil clean. This has been used in the past as an attempt to prolong the life of metal blades by minimizing the wear on them. Considering the above data, we now know that the additional squeegee force has no appreciable effect on paste pressure. This eliminates any remaining reason to increase blade pressure beyond the minimum required to clear the stencil surface.

Squeegee Speed

For the squeegee speed experiment, we used:

1. A 300 g roll of solder paste
2. A squeegee angle of 55 degrees
3. A pressure of 50 Newtons
4. Speed was varied from 30 – 90 mm/sec.

Again, paste pressure was measured throughout the print stroke and graphed as follows (Figure 8):

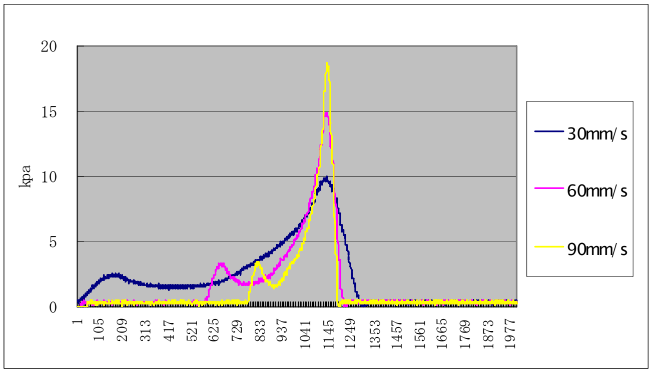

Figure 8. Pressure at Varying Squeegee Speeds.

The results are as expected:

As speed increases, we see a reduced time over which the transducer sees the pressure. This makes sense because the paste travels over the sensor much more quickly at faster speeds.

Additionally, as speed increases, we see a larger maximum pressure, which is seen in the actual values, below:

Squeegee Speed	Max Pressure
30 mm/sec	9.94 KPa
60 mm.sec	14.93 KPa
90 mm/sec	18.67 KPa

Table 4. Pressure at Various Squeegee Speeds.

The results make sense, as it takes more force on the stencil to push the paste up the face of the blade at a higher speed to maintain the rolling action of the solder paste.

Looking at the dramatic peak that forms at higher print speeds, we can better understand what happens during high speed printing. Typically, higher speed printing requires the solder paste to be “worked” or printed repeatedly to thin the paste down to a viscosity that allows it to roll.

A thicker paste will need a higher force to get it moving back up the face of the blade from the tip. The higher the pressure, the more likely that the tip of blade will be pushed up by the solder paste, causing a loss of contact with the stencil. The result is seen as the paste hydroplaning, or streaking behind the blade after it passes over it.

Efforts to eliminate this problem in the past have centered on increasing the squeegee pressure. This prevents the blade from hydroplaning (up to a point, until the blade is bent too far from excessive pressure). However, as we saw from experiment #3, this does very little to increase the filling pressure of the paste. The net result is that, even with the higher paste pressure, there is too little time that the pressure is applied to the aperture, resulting in insufficient filling.

DISCUSSION

As we can see from all of the data, the parameters with the greatest effect on Paste Pressure are (in decreasing order):

1. Squeegee Speed
2. Blade Angle
3. Solder Paste Amount
4. Blade Pressure

As a result, one would think that a faster squeegee speed would result in the best aperture filling during the print process. However, experience shows that it has the opposite effect: the potential for insufficient aperture fill, especially for larger apertures increases with increasing speeds.

As a result, it makes more sense to look at the aperture filling potential as the total area below the curve of pressure versus time, or

$$\int P\,dt$$

In a printing operation, it still takes a finite amount of time to fill each aperture. We can improve the filling of each aperture by increasing the time spent over it and/or increasing the pressure.

In this case, the parameters that have the greatest effects on filling *potential* are:

1. Blade Angle
2. Solder Paste Amount
3. Squeegee Speed
4. Blade Pressure

PRACTICAL APPLICATIONS

In a printing process, one has to not only worry about the potential for insufficient filling of the apertures (caused by low pressure & a small amount of time over the aperture), but also the potential for bridging to occur by too much pressure and/or time over the aperture.

So, what can we do to optimize aperture filling in the day to day printing process?

1. Optimize Blade Angle for Squeegee Speed

In a significant number of applications, print speed is dictated by a cycle time requirement. As a result, there needs to be a way to improve the time that the paste spends over the hole.

Reducing the blade angle will flatten the roll, increasing the contact area of the paste. This not only increases the maximum filling force, it also increases the amount of time the paste is over the hole.

From our studies, it appears that increasing squeegee force has little, if any consequence on the effective squeegee angle. Specifically, when we doubled the applied force of the squeegee and measured the resultant paste pressure, there was only a very slight increase in the overall maximum pressure reading obtained, correlating to a theoretical angle change of less than 1°.

To significantly adjust the blade angle with traditional solder paste printers, the options available are:

1. A mechanical modification to the squeegee head, or
2. Employing a different angle squeegee blade holder.

Neither one of these options provides much process flexibility on the production floor. Furthermore, they significantly increase the potential for set up errors.

Unless the machine is equipped with a means to change squeegee angle as a process parameter, there is no way to effect this change in the machine program. Without this ability, one does not have a way to make process changes to adapt to the routine destabilizing events such as a stencil wipe cycle, or a pause in the print cycle (i.e. for unscheduled downtime, or breaks).

2. Increase the Size of the Solder Paste Roll for Higher Squeegee Speeds

For printers that do not have the ability to change the blade angle, a secondary way to improve the pressure and time over the hole in a high speed printing operation is to optimize the amount of solder paste on the stencil.

A larger solder paste roll will have a higher applied pressure as well as a longer time that the pressure is applied. Too large a roll size for a given speed applies too much pressure to the aperture for too long a time, increasing the potential for bridging of fine pitch devices.

So, how do we optimize the paste rolls size on the stencil? As mentioned previously, there has been a quasi-control of this by focusing on the frequency and amount of solder paste dispensed via an automatic dispenser. However, it takes a significant amount of time to perform this dispense. As a result, paste dispense is typically infrequent, with possibly too much material dispensed each time.

True solder paste volume control can be accomplished in one of two ways: The first way is with an enclosed print head. The second way is to dispense more accurately and more often.

For an enclosed print head, the paste roll size is constant: it is the size of the paste chamber. The problem with this method is that there is no way to improve the time spent over an aperture without changing the print speed. In a short cycle time application, this might pose a problem.

The ability to precisely dispense a small amount of solder paste after every print or after a relatively small number of prints will keep the solder paste roll volume / diameter constant. Most printers do not have this option due to the long time required to dispense or the relative inaccuracy of the dispenser.

Although the printer that we used for these experiments had the ability to dispense every print cycle without an impact on cycle time, many other printers do not. Printer manufacturers need to spend more research on this overlooked part of the process.

During many of the print test experiments conducted in recent history, there has been a focus on starting every trial with a fixed amount of solder paste on the stencil. In this way, the results of the testing are much more consistent than what is normally found in production. Why wouldn't we apply this same logic to the production floor?

As the data shows, there is a significant difference in paste filling pressure when solder volume on the stencil is varied. Since we know that the printing process consumes solder paste from the stencil at a fixed rate (for a given board / stencil combination), we can calculate the usage over time.

For instance, if 2 grams of paste were used per print stroke, the operator could add 150 – 200 grams of solder paste every 75 boards, or the dispenser could put down 75 – 100 grams every 40 boards. In both cases, the amount is approximate, and over the course of a shift, the errors in the volume added to the stencil can add up over time.

The errors in an operator adding solder paste by hand are readily evident. Different operators will place different amounts of solder paste on the stencil. Furthermore, the same operator will not place the same amount down every time. This process has been used since the beginning of solder paste printing, and can lead to printing defects if the volume errors continue to multiply.

The errors in paste dispensing are also readily evident. Determining the exact amount of solder paste to be dispensed is not typically done when a board file is programmed. Instead, a single dispense profile is created and then the same settings are applied to all the other programs. In these cases, volume errors multiply, but now they do it at a fixed rate.

The paste dispensers themselves are not very accurate. Most are reciprocating bulk dispensers that apply air pressure to the back of the stopper in the cartridge. The time it takes to pressurize the cartridge varies significantly through its usage, depending on how much paste remains in the tube (See Figure 9). As a result, the actual amount of solder paste dispensed varies significantly from the first to the last dispense cycle. Lastly, when dispensing a large amount of solder paste with little paste remaining in the tube, the full amount required may not be dispensed, adding further error to the total amount of solder left on the stencil.

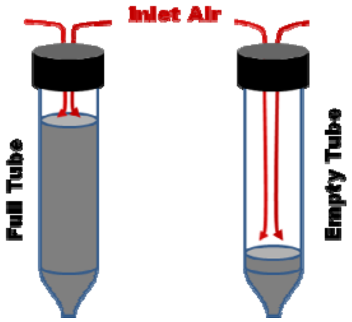

Figure 9. Illustration of Pressurization Difference Between Full and Empty Tubes.

The better designed paste dispensers place paste in the center of the roll and dispenses paste after only a few boards. The ability to adjust the required pressurization time depending on the percentage of material left in the tube minimizes the difference in the amount dispensed from the first to the last dispense in the tube. Since the dispenser does not move across the length of the paste roll, there is no cycle time penalty to dispense as often as necessary. Additionally, dispensing in the center of the roll minimizes the tendency for the paste to spread beyond the ends of the blades. This further minimizes the variation of the amount of material actually being printed.

The ability to cut the paste at the tube opening after dispense ensures that all of the paste that leaves the tube drops onto the paste roll. An automatic shutter covers the tube outlet, ensuring that no additional paste drops out of the tube in between dispense cycles.

3. Minimize the Amount of Paste Sticking to the Blades

One other factor in the effective solder paste roll size is the amount of paste that sticks to the blade. On a two blade system, the more paste that sticks to the first blade, the less paste that is available for the return print. As a result, it is not uncommon to see adequate print quality on one squeegee direction, but not in the other.

Much of this effect is due to the solder paste characteristics and the blade finish. Some solder pastes tend to stick more to the blades at colder temperatures. Additionally, some squeegee blade finishes are more prone to material sticking to them.

The ideal process has a single squeegee blade that flips over the solder paste roll in between prints, keeping the paste on only one side of the blade. This minimizes the effect of paste sticking to the blades because the paste is available on the same side of the blade for the return print. Using a squeegee with a durable, low friction surface finish minimizes this effect further.

CONCLUSION

A robust screen printing process requires that we control as many sources of variation as possible. Of course, not all of these variables are easy to control, but it is helpful to understand which ones are the largest sources of variation and target these.

From the testing performed, we have learned:

1. Blade angle affects the overall time the paste spends over the aperture, as well as the maximum filling pressure. Both of these characteristics have a significant effect on the resultant aperture fill.

2. The volume of solder paste on the stencil has a similar, but slightly smaller effect on aperture fill.

3. In operations where a change in blade angle is not possible, the volume should be controlled more tightly to control the overall aperture fill. This is most easily done with more frequent, more precise dispense cycles.

4. Increasing speed has the most dramatic effect on print pressure. Since these effects are felt on the aperture for a much shorter amount of time, the net result is that the potential for insufficient aperture fill (especially for large apertures) increases with increasing speeds.

5. The minimum squeegee pressure necessary to completely wipe the surface of the stencil clean should be used all of the time, as squeegee force has little, if any, effect on the overall filling force.

Controlling these important parameters is not an easy task with many of today’s printers. However, as we continue to push the envelope into smaller and finer pitch devices, it becomes even more critical to fully understand and minimize the effects of even the smallest variation.

ACKNOWLEDGEMENTS

I would like to thank Mr. Kouichi Sumioka of Yamaha Motor Corporation, for the stencil design used in this application, as well as for setting up the experiment and collecting the data. The results of his work were instrumental in his design of the more precise, stationary solder paste dispenser described in this article.

---

[1] George Babka, Scott Zerkle, Frank Andres, et. al. "A New Angle on Printing." Global SMT & Packaging February, 2009: pp. 36-39.