The first lesson of stencil printing small apertures is:

“DON’T JUST ACCEPT THE PASTE FILE FROM THE DESIGNER”

It seems that each generation of assemblers forgets the physics of how a stencil print works. The printers continue to get smarter and more accurate, but they cannot defy the basic laws of how the process works. In my consulting, I am more and more being told that the stencil file is just sent to the stencil maker with no real rules about what they are to do. Or, if there are rules, they are generic and steeped in tribal knowledge.

The basic process is as follows:

- The Squeegee action across the stencil surface fills the aperture with solder paste
- The paste contacts the underlying PCB pad and the flux in the paste adheres to the pad
- The stencil snaps away from the PCB pad
- Gravity and the flux adhesion to the PCB pad hold the solder paste slug as the stencil moves away

Modern printers are doing a very credible job of “filling the aperture” with solder paste, and cleaning the underside of excess paste. But, beyond these machine-specific tasks, the stencil print is reduced to a battle of forces.

The short list of these forces are:

- The force of gravity acting on the mass of the solder “slug”
- The adhesion forces holding the solder paste to the sidewall of the stencil
- The adhesion forces attaching the solder paste “slug” to the underlying component pad

Each of these forces is further modified by:

- The ball size
- The flux to solder ratio
- The viscosity of the flux
- The speed of the “snap off”
- The method of preparation of the stencil aperture sidewalls

A basic review of the process shows why neglecting to modify the stencil files is a prescription for decreasing yields as the size of the aperture decreases.

With large apertures the adhesion to the pad (aided by gravity) swamps the other forces. However, as the area of the aperture is successively reduced, then the “adhesion forces holding the paste to the sidewall of the stencil” begin to dominate. At some point, these sidewall forces inhibit the ability to print the solder paste through the aperture.

There is nothing new in this situation. Process engineers of prior generations determined that you must maintain a 1/3 to 2/3 minimum ratio between the surface area of the stencil sidewall (1/3) and the area of the opening (2/3). However, this is a very rough rule of thumb because it does not account for the effective adhesion of different surface finishes. When this ratio was generally accepted, the prevalent surface finish was HASL. Today, the really small apertures for 0201’s or 01005’s often have an ENIG finish, which is much “slicker”, and there are more options for the ball size in the paste.
However, if we use the 1/3 ratio, we can at least define a beginning rule for the smallest apertures that should be used with given stencil thickness. If we assume that the stencil is 4-mil thick and the aperture is square, then we can write a formula as follows:

- Area of the side wall is 4 times the area of rectangle of height 4 mils and length of “X”.
- Therefore, a single side of the aperture would be:
  \[ A_s = 4 \times X \]
- And the area of the four sidewalls would be \[ 4 \times 4 \times X \]. Or, \[ A_{st} = 16X \].
- The area of the opening (being a square with equal sides) is \[ X \times X \] or \[ X^2 \].
- Now, using the 1/3 to 2/3 ratio, we can create an inequality between the two areas and solve for “X”.
  \[ \frac{X^2}{16X} > \frac{2}{3} \]
  \[ X > \frac{2}{3} \times 16 \]
  \[ X > 10.6 \text{ mils} \]

Using the same formula, we can solve for the minimum dimension of a rectangular area of a 3-mil thick stencil

- \[ X > \frac{2}{3} \times 12 \]
- \[ X > 8 \text{ mils} \]

It is necessary to convert these simple ratios back to an area because not all apertures are square. The area tells us that:

- The minimum area for a 3 mil stencil is \(8 \times 8 = 64\) square mils, and
- The minimum area for a 4 mil stencil is \(10.6 \times 10.6 = 112.36\) square mils.

In order to give these “minimum areas” a reasonableness test, we should look at the pad size of the smallest component currently in mass production, the 01005. Depending upon the data sheet that is referenced, the pad size for 01005 is approximately 11 mils on a side or 121 square mils.

_Interestingly, the pad area for 01005 indicates that you cannot use a 4 mil stencil and expect to get reasonable results!_

If we carry this ratio of areas a little further, you must ask the question about some of the very common small pads for BGAs. Many of these are 9 mils in diameter.

- The paste file from the designer will show a pattern of round 9 mil pads.
- How should these be stencil printed?
- Is this the correct pattern for the stencil printer?

The area of a 9 mil round aperture is \[3.14 \times (3.5)^2 = 38.465\] square mils. This is below the 64 square mils minimum aperture opening for good deposition with a 3 mil stencil. However, if we were to change the round aperture to a square of 9 mils on a side, we exceed the ratio needed for the 3-mil stencil as this square pattern increases the area to 81 square mils.

We must further question why we are using a round aperture. Keep in mind that the solder paste is composed of round balls of solder. We may think of it as being more like tooth paste, but it is not. Because of the round balls, the deposition of the solder through the aperture must be in “complete
balls” of solder. We cannot have a fraction of a ball. The ball size of a given type of solder is actually a range. However;

- The average diameter for a Type 4 solder paste is 1.14 mils.
- The average diameter for a type 3 solder paste is 1.38 mils.

If we further consider that we cannot extrude a partial ball, our minimum area takes on further constraints.

*For maximum solder deposition, the aperture opening should have sides that are a multiple of the average diameter of solder type to be extruded.*

We have determined that for a 9 mil round pad, we should use a maximum of a 3 mil stencil, with a type 4 paste. Let’s examine our selection of sides of 9 * 9, (a rectangle instead of round), we find that our 9 mil side can only “line up” 7 Type 4 solder balls with a diameter of 1.14 mils, which reduces the theoretical volume we are achieving by more than 10%. Therefore, our minimum aperture dimension for a 9 mil pad, with a 3 mil stencil and a Type 4 paste should actually be 9.5 to 10 mils. This dimension allows us to have a solder matrix of 8x8 solder balls, but only two rows high. (A ball diameter of 1.14 mils in an opening that is 3 mils high, cannot have more than two rows of solder balls.

If we calculate the solder volume on this 9.5 x 9.5 mil aperture, we find that we have two rows of 8x8 or 128 total solder balls. This then yields a (again theoretical) volume of 2.28 mil (height) X (8*1.14) 2 =189.6 cubic mils.

*It is important to note the final volume of melted solder will be significantly less than the rows of solder balls stacked on top of each other.*

If the solder paste were indeed a “paste”, the volume in 9.5 x 9.5 x 3 aperture would be 270.75 cubic mils.

*Whew!* So, with a Type 4 paste, on a 9 mil round pad, using a 3 mil stencil and a square aperture of 9.5 x 9.5 mils, our max volume is only 70% of the theoretical (189 compared to 270 cubic mils).

Now, compare this volume to what would be achieved using a round aperture of 9 mils. We know from the volume analysis that we violate the ratio of aperture opening area to side wall area very significantly even with a 3 mil stencil. But, it gets worse since our solder paste is composed of round balls. If we draw a circle of 9 mil in diameter and then fit in the number of 1.14 mil solder balls, we find we can only get 45 solder balls in a layer, and still only two layers deep (or 90 total solder balls).

The reason for this daisy chain of math is to show just how much the deposition of solder paste can vary from the expected when we are pasting small parts.

*The lesson to take away is don’t use round apertures for small features and be certain that you fully examine the volume of paste that can be achieved with a given stencil design.*

Respectfully,

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