Whitepaper
Assembly of 0201 Components

Introduction

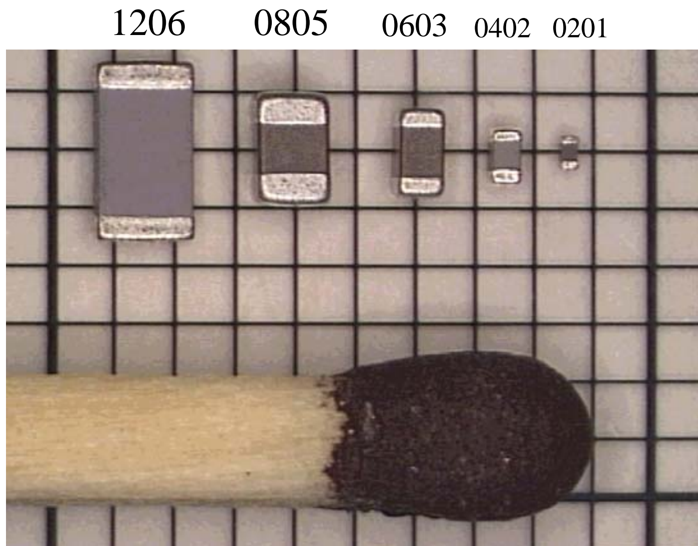
As the drive toward miniaturisation in electronic assembly continues, and Surface Mount Technology matures, components become ever smaller and lighter. Although the prevailing sizes in passives were 1206 and 0805 in the 1980's, these no longer make up the majority of the soldered passives at this time.

Whereas they are only beginning to emerge at the present time, 0201 packages are expected to claim a fair portion of the market in the next few years. With their size of only 0.6 mm by 0.3 mm, and their low mass, these packages allow for considerable reduction of board area and weight with respect to the 0402 package. Figure 1 shows the relative sizes of the component packages ranging from 1206 to 0201.

Apart from the apparent advantages, however, there are also a few other points that must be taken into account when considering implementing 0201 packages into a given process. For one, an 0201 capacitor, for example, cannot have the same capacitance as a larger package, simply because of its size. The maximum capacities for the different packages at this time (this may be subject to change) are shown in figure 2.

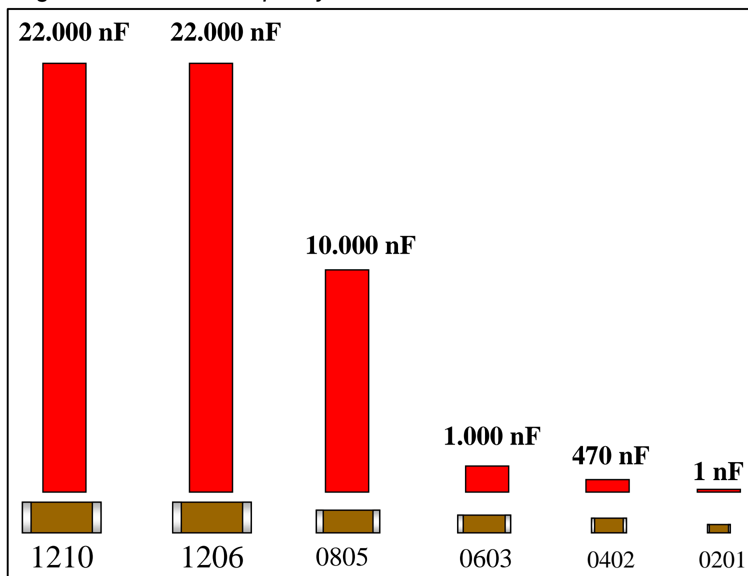
PHILIPS Assembléon

Figure 1: Capacitor range



Furthermore, a component as small as the 0201 may require adaptations of the reflow assembly process. This new platform incorporates the 0201 package in the improved board technology, defining, amongst others, the board layout to be used; the manner in which these rules are achieved is described in more detail in Chapter.

Figure 2: Maximum capacity available



As soon as tentative layouts have been defined for a new component such as the 0201 package, these have to be tested. For the 0201, this was done by means of an alpha run (verification study), in which over 27 thousand of these components were assembled on the new derived layout, and inspected for defects. The experiments are described in more detail in Chapter.

To test the placement machine's capability of placing 0201 components, the number of refires during assembly of the alpha run was taken from the Manufacturing Information System (MIS) data.

One serious potential defect that was investigated more in-depth is that of tombstoning. Tombstoning - also referred to by other imaginative names such as drawbridging, the Stonehenge effect, and the Manhattan effect - involves one of the component' ends being lifted off the board so that no electrical connection is made at that end. This occurs when the solder paste at one component end melts, and the force due to the surface tension in the meniscus is not countered by opposing forces at the other end. In a normal, symmetrical, situation, the forces will always balance; so lack of wetting at one of the component ends is a requirement that must be met for this to happen. Common causes are:

- component placement errors, in which one of the component ends does not make contact with the solder paste,
- misplaced solder paste deposits, or deposits with the wrong shape, so that they do not make contact with the component, and,
- temperature differences between the solder paste deposits at the two ends. If one paste deposit melts and forms a meniscus before the other, the component may be rotated before the forces can balance. Note that this cause is much less likely.

In order to test the 0201 components' sensitivity to tombstoning, an experiment was carried out in which a number of components was placed on one solder land only, with the other component end resting on the solder resist layer on the board.

Luckily, the forces due to the surface tension in SMT may also work to the manufacturer's advantage. The meniscus formed between solder lands and component metallisation when the solder paste goes liquid, for example, may also give rise to forces in the plane of the board. Previous work [1, 2] has shown that chips are particularly sensitive to this. If chips have been placed off-centre with respect to the solder lands, the surface tension force in the molten solder may succeed in pulling them completely or part of the way back onto the solder lands; this is referred to as self-alignment. Thus, it may not always be necessary to place components perfectly on the solder lands, and the requirements on the placement accuracy of 0201 chips may not be as high as would originally be expected. Therefore, experiments to test the self-aligning abilities of 0201 components were also carried out: components were deliberately placed at offsets, and their final positions after reflow were inspected.

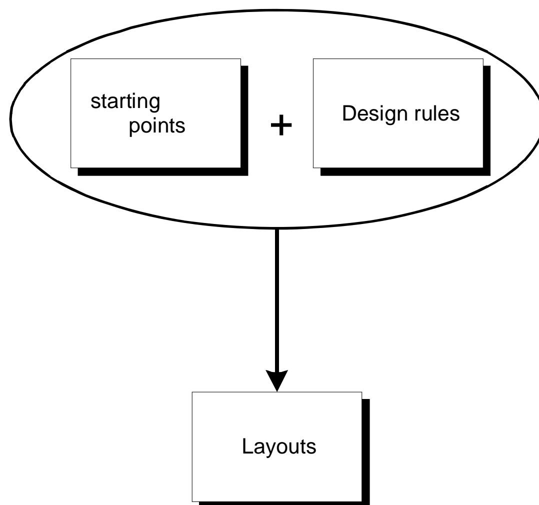
The self-alignment discussed in the previous paragraph deals with one component and its position relative to the solder lands. What if two components are placed so close together that they make contact after placement, will they still make contact – forming a short circuit – after reflow, or will the self-aligning forces drawing them to their respective solder lands separate them? This was tested for 0402 and 0603 components, to have an indication of what may happen with 0201 components.

Deriving the Layouts

When the layouts are defined for a new component, they are based on two sources of input:
- The starting points with respect to board technology and process conditions
- The design rules

This is shown schematically in Figure 3.

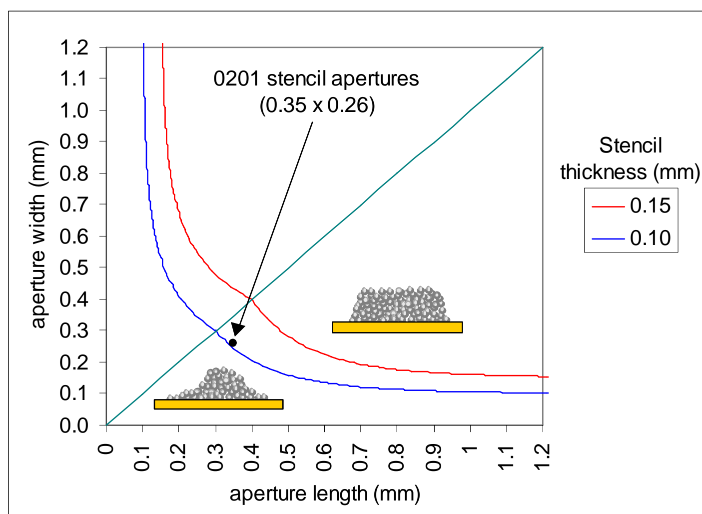
Figure 3: Sources of layouts



Starting Points for the Layouts

For the generation of the layout of the 0201 components, the state of the art board technology is taken as a starting point. With respect to the process conditions, printing of reproducible solder paste deposits is one of the key factors for successful assembly of 0201 components.

Figure 4: Required stencil aperture dimensions within the defined boundaries

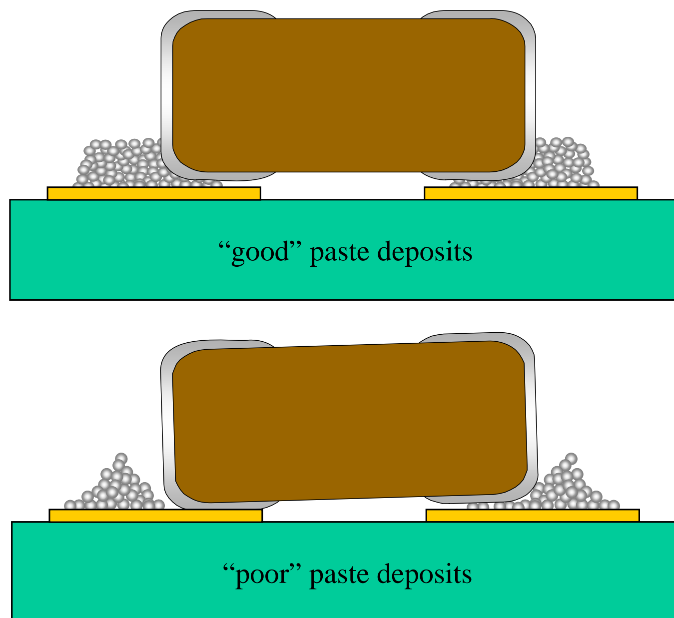


If a stencil aperture has a width of 0.3 mm and a length of 1 mm, it lies well above the line corresponding to the 150 μm-thick stencil. This means that the solder paste deposits should release well from the stencil aperture, and have a trapezoidal shape that is something like the one above the red curve in *Figure* .

When a 150 μm-thick stencil is used, and the aperture width is 0.3 mm, the minimum aperture length should lie around 0.5 mm. If the length is smaller, the aperture falls below the line for the 150 μm-thick stencil, and the paste deposits may not always have the desired "good" shape. If solder paste deposits achieve the desired height but have the "poor" shape shown at the bottom in , a slight component offset may give rise to improper contact between the component metallisation and the solder paste, particularly if the component corners are rounded, as with a capacitor. This is the case at the left end of the lower component in . The component may then not be properly wetted during reflow, thereby increasing the probability of defects.

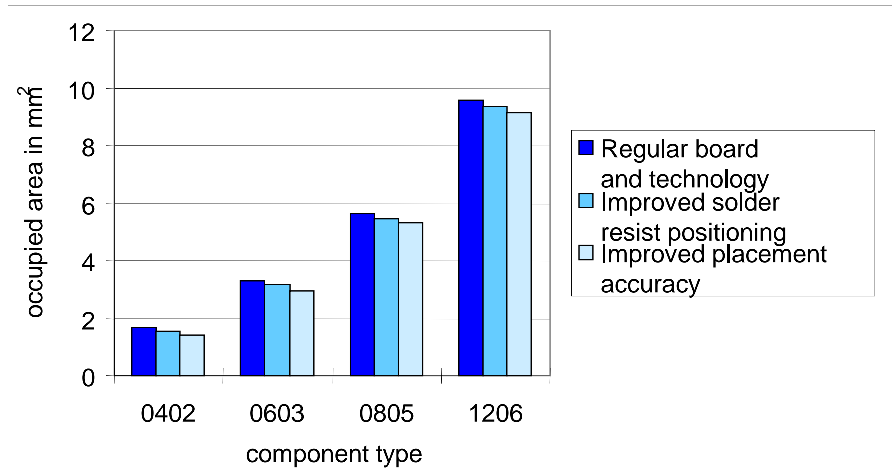
The 0201 stencil apertures are defined as 0.260 mm × 0.350 mm. As shown by the dot in *Figure* , this puts the 0201 just above the line belonging to the 100 μm-thick stencil; i.e. 100 μm is the preferred stencil thickness for this component, and using it should result in good solder paste deposits, provided that the process is controlled. If the 0201 components are to be combined with larger components, which require more solder paste than the 100 μm-thick stencil can deliver, it may be necessary to use a thicker stencil nonetheless. In that case, one must be aware that there is a higher risk of poor solder paste deposits for the 0201, with the subsequent larger probability of defects.

Figure 5: Placement on "good" and "poor" solder paste deposits



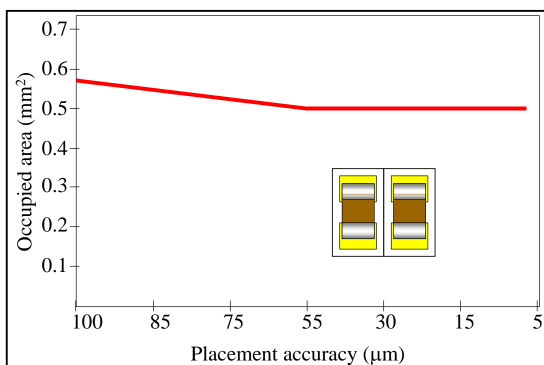
Just as the solder land layouts partly determine the stencil apertures - and the (preferred) stencil thickness - they also assist in determining the occupied area. In order to prevent defects arising from components that have been placed too close to each other (primarily short circuits), a "no-man's-land" is defined around every component solder land layout, which is off limits for other components – this area must remain free. This border plus the solder lands themselves – the total area taken up by a single component – is referred to as the "occupied area." Components may be placed no closer to each other than with the occupied areas just touching.

Figure 6: Reduction of occupied area for passive components



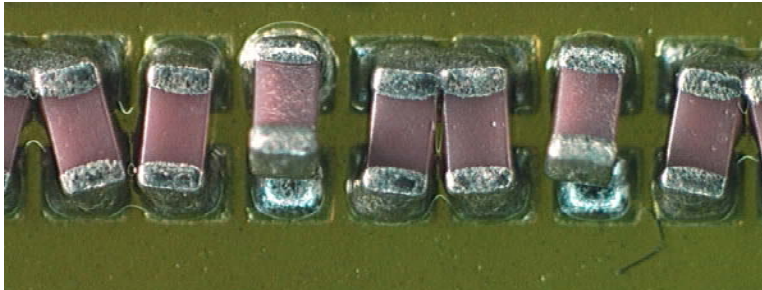
In the light of continuing miniaturisation, it is desirable to minimise the occupied area for a given component. This can be achieved in a number of ways, two of which are illustrated in . The darkest blue columns represent the occupied area for a number of chips, according to the present-day board technology (this example does not include 0201, as these are first included in the more sophisticated board classes). In present-day technology, the solder resist positioning must be accurate within 75 µm; that is, it may not be more than 75 µm off-centre in any one direction. If, however, the solder resist were instead to be positioned with an accuracy of 50 µm, the occupied area for all components could be lowered somewhat, as shown by the middle bars for each component in . If, furthermore, the component placement accuracy could be improved from 150 µm (as specified in regular placement machines) to 90 µm, the occupied area could be further reduced to the lightest blue columns.

Figure 7: Occupied area of an 0201, as a function of the placement accuracy



Even if a parameter can be improved infinitely, however, there is an end to the corresponding reduction of the occupied area. Even if the placement accuracy, for example, can be improved such that components are always placed “perfectly,” there will have to be a certain minimum occupied area, see **Error! Reference source not found.**. Beyond a particular placement accuracy, further improvement will not yield a smaller occupied area, as will be illustrated below.

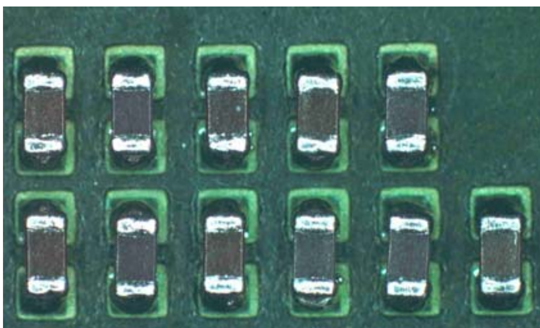
Figure 8: Soldering 0201 components, disregarding the occupied area



The importance of a certain minimum occupied area was shown by means of an experiment with detrimental results. In this experiment, of which the results are shown in **Error! Reference source not found.**, the occupied areas were ignored, and the solder lands were placed closer together than is allowed according to the layout rules based on the defined process conditions. Placement was no problem: the placement machine could set the components down on the solder lands quite accurately, and there were no optically discernible defects. The result after reflow, however, is disastrous. The number of defects was countless, with components that had been lifted at one end (tombstoning) and components that formed short circuits.

When the same components were soldered on the same solder land layouts, but using the occupied areas prescribed by the correct calculation rules , the result was as shown in . Apparently, something happens during the reflow stage, which moves the components about. Slumping of the solder paste, jerking of the components as the meniscus is formed, and so-called “swimming” of the components on pools of molten solder can - apparently - all move the components enough that they make contact when the occupied areas are ignored. Apparently, living up to the layout rules with respect to the occupied area costs some extra area, but it keeps the components far enough apart to avoid such defects.

Figure 9: Soldering 0201 components with the correct occupied area



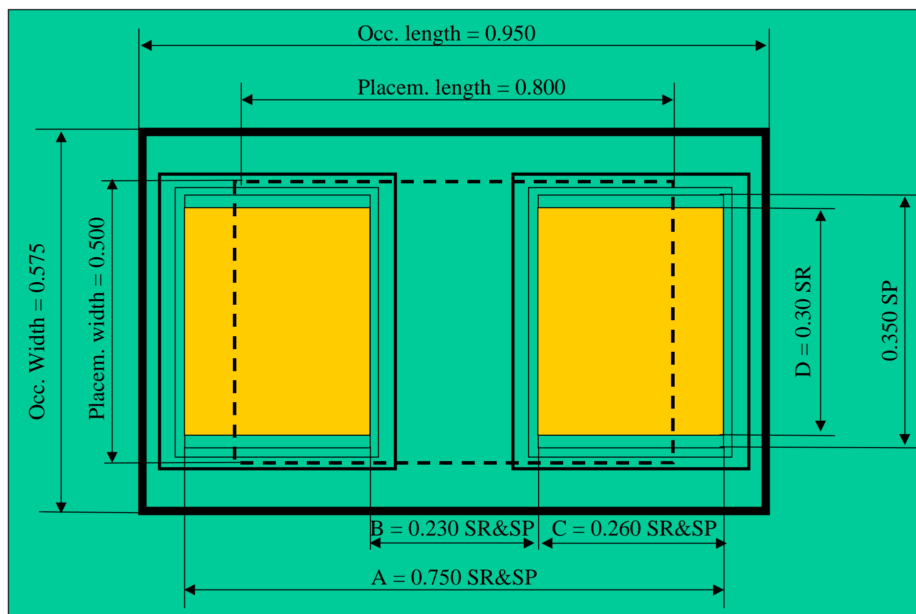
Layouts for 0201

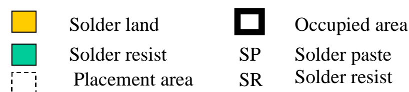
Thus, the 0201 design rules are attained in the fashion outlined in the previous section. These design rules are then combined with the starting conditions, to result in the 0201 layouts.

What, then, are these layouts? They are summarised in .

- The solder lands are 0.26 mm by 0.3 mm – note that they are solder resist defined. The solder resist dimensions (and thus also the solder land dimensions) are denoted with "SR." The copper extends underneath the solder resist layer.
- Solder paste deposits ("SP") should be 0.26 mm by 0.35 mm; the solder paste deposit is as long as the solder land length, and wider than the solder land width, i.e. there is over-printing in one direction.
- The component should be placed within a rectangle that is 0.8 mm by 0.5 mm – recall that the component dimensions are 0.6 mm by 0.3 mm, leaving some room for misplacement.
- The occupied area, finally, is 0.95 mm by 0.575 mm.

Figure 10: Optimized footprint for 0201





Experiments

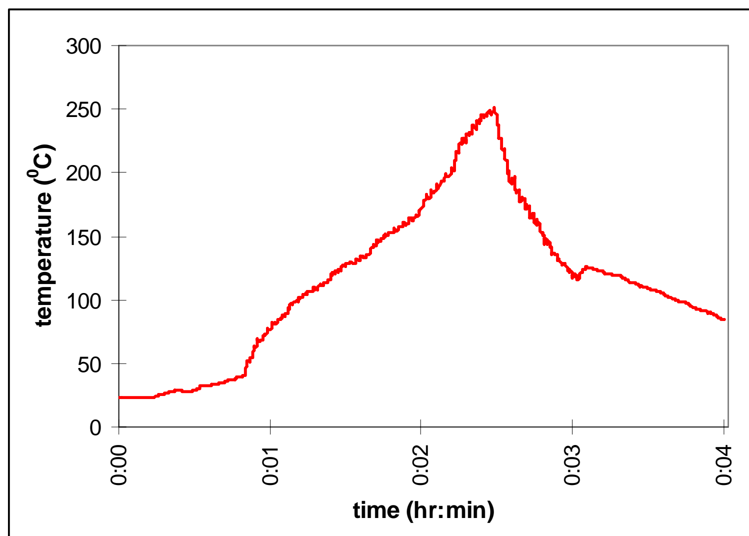
As described in the Introduction, a number of different experiments was carried out in this project. After the tentative layout rules were established for 0201 components, a large alpha run (verification study) was done to estimate the number of defects that is to be expected when these layout rules are applied in the reflow process. The placement machine's capability of placing 0201 packages was checked by taking a closer look at its Manufacturing Information System data from this alpha run.

Component sensitivity to tombstoning on these tentative layouts was tested by placing the components on one solder land only, and the component's self-aligning ability (i.e. the importance of accurate placement with respect to the component's final position after reflow) was investigated by placing the components at programmed offsets with respect to the solder lands. The probability that components touching their neighbours are separated by self-aligning forces was studied by placing components such that they made contact. The experiments are described in more detail in the following sections.

Alpha Run

The purpose of this experiment was simply to mount a large number of 0201 packages onto FR4 boards, in the defined assembly process, and to find the resulting defect level.

Figure 11: Temperature profile for alpha run



The board, when fully assembled, holds 302 of the 0201 components. Due to problems with one of the placement modules, some boards were not completely assembled; these have only 249 instead of 302 of these components. A total of 40 boards was assembled completely, and 12 were assembled incompletely, leading to 15,068 reflowed 0201 components.

Furthermore, 0201 components were also mounted on other FR4 boards with different board layouts, but where the 0201 layouts are identical to the first board. Apart from the boards used, the process was identical to the first board. Another 12,096 of the 0201 components were assembled here.

Thus, summing the 0201 components mounted on the two different board layouts, we arrive at a grand total of 27,164 mounted 0201 components.

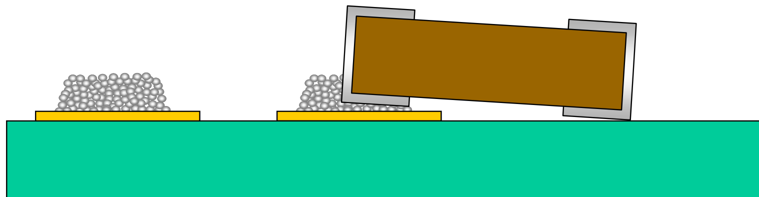
The Manufacturing Information System (MIS) data obtained from the placement machine were used to determine the number of refires when placing 0201 components, during the alpha verification run. Not all assembled boards were part of the alpha run; therefore the number of 0201 components in the MIS data is larger than the number included in the description of the alpha run in this report.

Tombstoning

In order to test the 0201 components' sensitivity to tombstoning, components were placed on one solder land only, with the other end resting on the board, as shown in Figure 12. A few parameters were varied in the experiments:

- 0201 capacitors and resistors were both included in the experiments. The difference in component height and metallisation shape could give rise to different behaviour with respect to tombstoning
- as μvias may have to be incorporated in the 0201 solder land layouts, and their effect on tombstoning is unknown, experiments were done with and without μvias
- for comparison of the 0201's sensitivity to tombstoning to that of larger packages under identical circumstances, 0402 and 0603 packages were also included in the experiments

Figure 2: Components placed on one solder land only



The experiments were carried out on FR4 boards with 0201, 0402, and 0603 solder land layouts according to the defined layout rules. One board had ten layouts with μvias, and ten layouts without μvias, for each of the three package sizes. Alpha Metals LR 735 R solder paste was printed onto the boards using a DEK 265 printing machine and a 100 μm-thick stencil. The solder paste was applied using double printing strokes (two strokes to a board), and the screen was cleaned after every three boards. The 0201, 0402, and 0603 chips were then placed with a Philips ACM-micro placement machine - five resistors and five capacitors were placed on the ten layouts with μvias, and likewise for the ten layouts without μvias, and this was repeated for the three package sizes. All three package types were given a specific offset such that the metallisation at one end was centred on a solder land, and the component's other end rested on the solder resist layer on the board. The boards were then reflowed in a modern standard (forced convection) reflow oven.

A total of 22 boards was assembled this way for the 0201 packages, and 23 boards for the 0402 and the 0603 packages. With five components in an identical setting (capacitor or resistor, μvia yes or no) per board, this leads to the totals listed in Table 1.

Table 1 Number of components with identical parameter settings, in tombstoning experiments

Component	R, no µvia	C, no µvia	R, µvia	C, µvia
0201	110	110	110	110
0402	115	115	115	115
0603	115	115	115	115

Self-Alignment

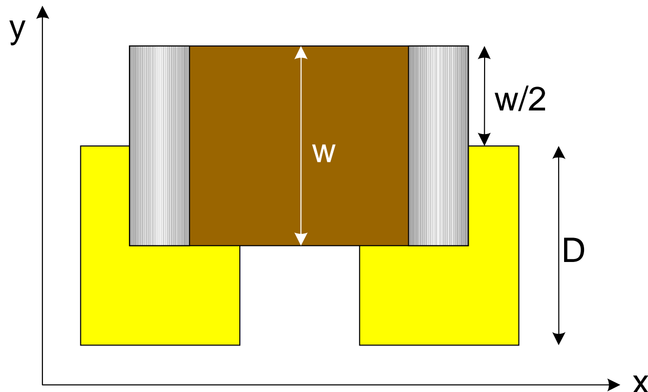
The degree to which components are capable of self-alignment was investigated by placing components at pre-programmed offsets; but first Alpha Metals LR 735 R solder paste was printed onto FR4 boards using an MPM UP 3000 paste printing machine and a stencil with a thickness of 100 µm. Boards with two different solder land finishes were used: the regular Nickel-Gold, and Copper. Furthermore, solder lands with and without µvias were included in the experiments. Unfortunately – and unintentionally - another parameter was also varied, as approximately one-third of the boards was supplied by supplier A, and the rest was from supplier B.

Components were placed on the boards. For purposes of comparison, 0402 and 0603 components were included in the experiments as well as the 0201 components, and both the resistor and capacitor versions were used for all three package sizes. The following 0201 components were mounted on a single board:

- five resistors on solder lands without µvias,
- five resistors on solder lands with µvias,
- five capacitors on solder lands without µvias,
- five capacitors on solder lands with µvias,

and the same for the 0402 and the 0603 package sizes.

Figure 3: Offset 50% in the y direction



The components were placed at programmed offsets of 100 μm in the x direction (see), 100 μm in the y direction, and 50 % in the y direction. The latter means that components were placed such that they were halfway off the solder lands in the y direction, as shown in 3. This involved the following absolute offsets:

- 0201: 150 μm
- 0402: 250 μm
- 0603: 400 μm

The component package, metallisation type (R or C), and the presence of a μvia were all varied on one board, and ten boards were assembled for each of the three offsets. This was repeated for the two board finishes, such that a total of 60 boards was assembled. All of the boards with the offsets in the x direction were from supplier A, and all but four of the boards with offsets in the y direction were from supplier B. All parameter variations (except for the board supplier) are summarised in Table 2 – fifty components were assembled with each of the possible combinations in the table, leading to a total of 3600 soldered components.

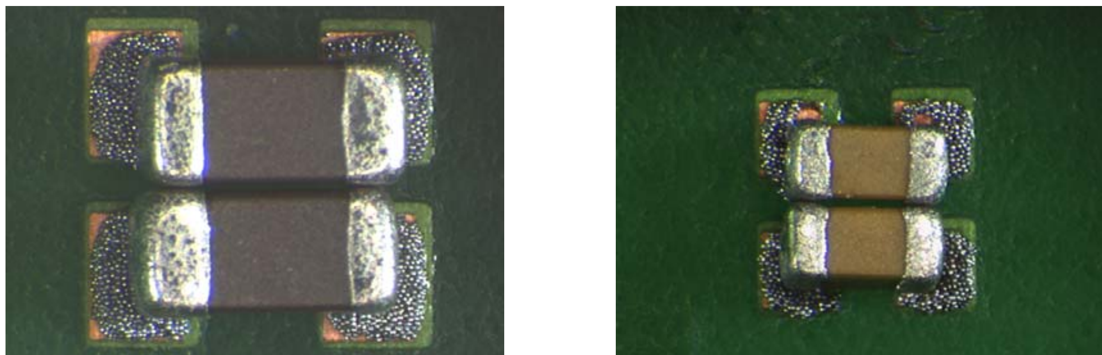
Table 2 Parameter variations in self-alignment experiments

Package	R/C	μvia	finish	offset
0201	R	no	NiAu	x 100 μm
0402	C	yes	Cu	y 100 μm
0603				y 50%

In order to test whether self-aligning forces will separate components that touch after placement, an additional experiment was carried out with 0402 and 0603 components. Recall the results of the experiment described in Chapter 0, which proved that disregarding the occupied area for 0201 components gave rise to an overwhelming number of defects, whereas these defects were not seen when the occupied area was according to the defined layout rules. Are these defects due to contact between neighbouring component metallisations, or due to contact between neighbouring solder paste deposits? More specifically, what if the occupied area is according to the defined layout rules but the components make contact after placement, due to placement errors? Will there be short circuits after reflow? Or will the self-aligning forces separate the components?

In order to test this, 0603 and 0402 capacitors were placed on neighbouring solder land layouts, that were at maximum proximity while still complying with the defined layout rules, using the placement machine in question. Next, the components were manually moved, using tweezers, such that they made contact, as shown in . The boards were then reflowed. A total of 120 pairs of each of the two package sizes was reflowed in this manner.

Figure 4: Components (0603 on the left, 0402 on the right) that just touch eachother after placement

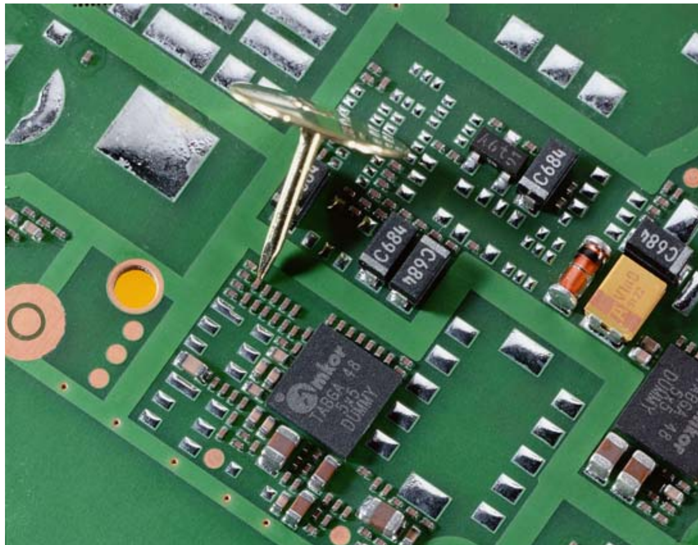


Results

Alpha Run

The results of the alpha verification run were straightforward and encouraging: zero defects were found. shows a close-up of one of the assembled boards; the tack points at a group of 0201 components close to a BGA.

Figure 5: Assembled X16 DB board with 0201 components



A total of 27,164 mounted 0201 components means 54,328 soldered connections; with zero defects, the defect level can then be assumed to be less than 55 ppm (95% confidence level).

Tombstoning

Not a single component was found even slightly lifted off the board. The occasional component had rotated slightly in the plane of the board; these components still rested on the board, however, so this is definitely not a sign of tombstoning. Furthermore, these components nearly always had an angle after placement (before reflow), as was supported by the flux outline around the component.

Self-Alignment

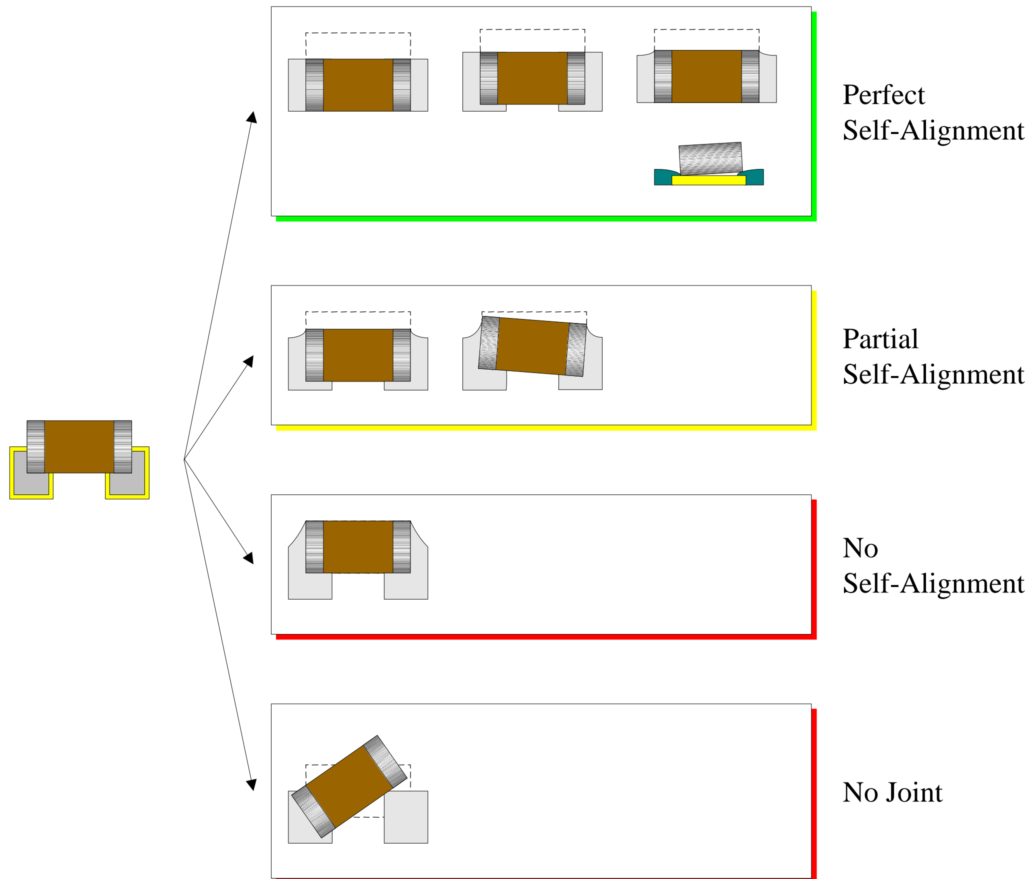
The best way to compare the results for the various parameter settings in this experiment would have been by comparing all components' measured offsets after reflow. A quick inspection soon pointed out, however, that this was not feasible for the 0201 components - the solder meniscus at the component ends made it very difficult to make out the exact location of the component corners. Measuring the locations of these corners through a microscope would undoubtedly result in such a high uncertainty in the calculated component offset that this was pointless. Therefore, a different approach was adopted: all components were visually inspected through a microscope, and their final positions were classified as belonging to one of the following four categories:

- Perfect self-alignment - the component drifted so far back onto its solder lands that it could not

be expected to move any further. In some cases this meant that the component was positioned perfectly on the solder lands; in other cases that it was within the solder lands but not perfectly centred on the footprint. There were also instances, however, in which the component appeared to be slightly wider than the solder lands. In this case, one component side was lodged against the solder resist layer (recall that the solder lands are solder resist defined!) while the other side was still up on the solder resist. Shifting the component any further would have involved lifting one side up onto the solder resist, which is, naturally, not likely to happen. Therefore, this situation was also defined as "perfect self-alignment."

- Partial self-alignment - the component had obviously moved from its original position, but had not achieved perfect self-alignment. Flux remnants on the board usually marked the components' initial positions, so that even a slight movement was easy to recognise.
- No self-alignment - the component remained just as it had originally been placed.
- No joint - one (or possibly both) of the component sides did not make a good joint with the solder land.

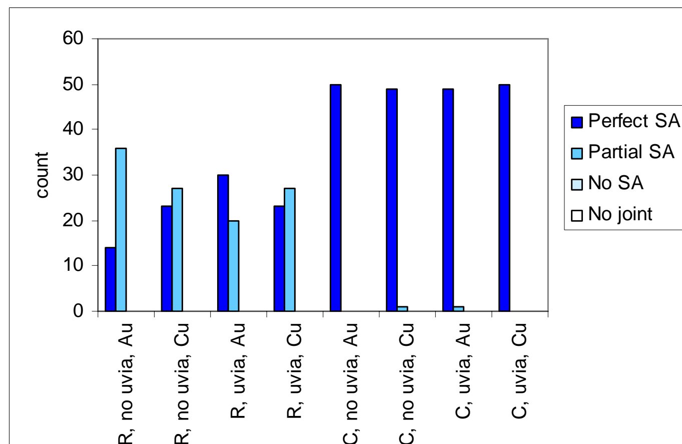
Figure 6: Categories for self-aligned chips



The results were all compared in graphs such as the one in 7. This particular figure shows the results for the 0603 components placed at an offset of 100 μm in the y direction, for all possible parameter combinations. Judging from the bars, there appears to be no significant difference between the components placed on solder lands with or without μvias, nor does there appear to be a difference between the two finishes, Copper and Nickel-Gold. There is, however, an obvious difference

between the R and C components - nearly all of the capacitors aligned perfectly, whereas roughly half of the resistors remained partially off the solder lands.

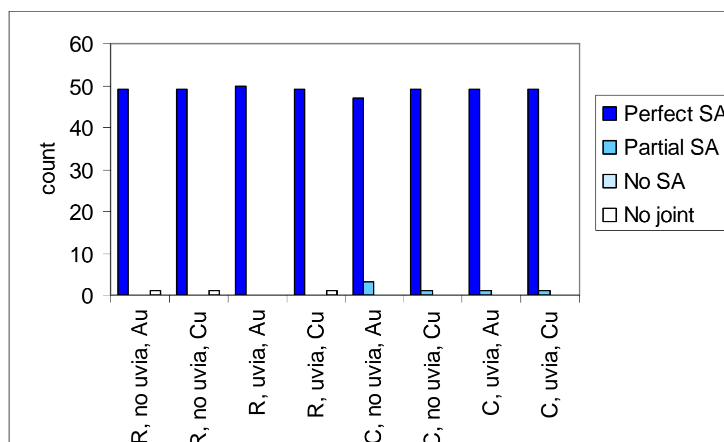
Figure 7: Results for 0603 components at 100 μm offset in y



Although they will not all be shown in this report, such graphs were also made for the 0603 components at the other two offsets, and for the 0201 and 0402 components. There was never a significant difference between the solder lands with or without μvias, or between the two board finishes, so the results for these parameter settings were all combined. This left three variables: the package size (0201, 0402, or 0603), the package metallisation (C or R terminals), and the offset.

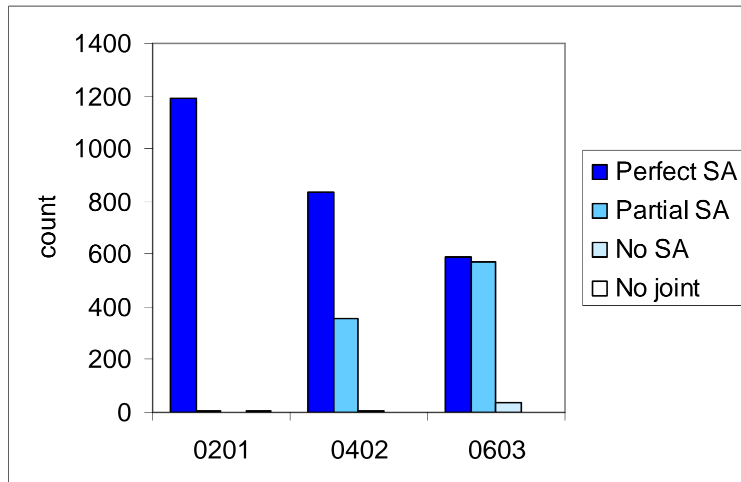
At this point, a few descriptive comments of a general nature on the 0201 results – the subject of this report, after all – are in order, before plunging into a detailed comparison of the remaining parameter settings. Nearly all 0201 components self-aligned perfectly. All of the components placed with an offset in the x direction were assigned to the category "perfect self-alignment," and only one of the components at an initial offset of 100 μm in the y direction did not self-align: it formed no joint on one side (probably due to poor wetting). The results for the components placed at an initial offset of 50 % (150 μm) in the y direction are shown in Figure - a total of nine components (out of 400) did not self-align perfectly.

Figure 8: Results for 0201 components at 50 % offset in y



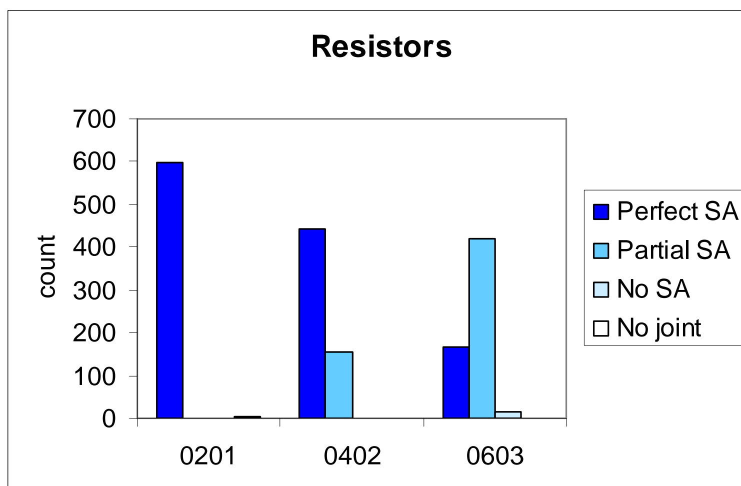
The 0402 packages proved to be less eager self-aligners than the 0201 packages, the capacitors in particular. Of the 0603 components, on the other hand, the capacitors are the better self-aligners, although the 0603s' overall score is lower than that of the 0402s.

Figure 19: Comparison of package sizes



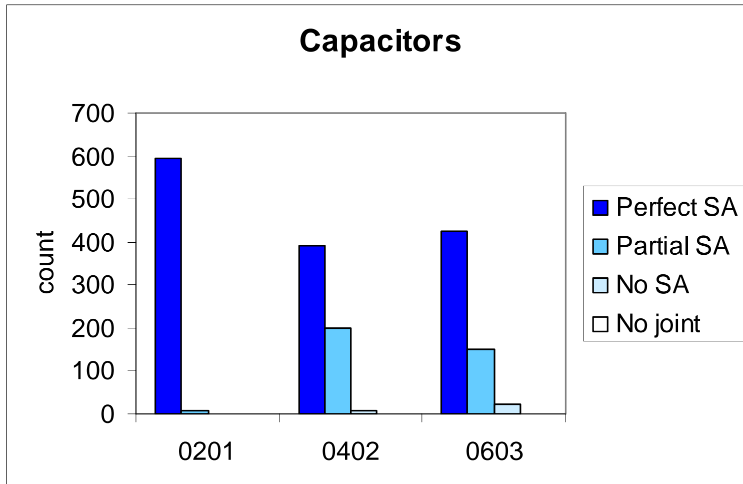
shows the results separated only by package sizes; all results for the board finishes, presence of μvias, the metallisation shape, and the three different offsets, are combined.

Figure 20: Comparison of package sizes – resistors only



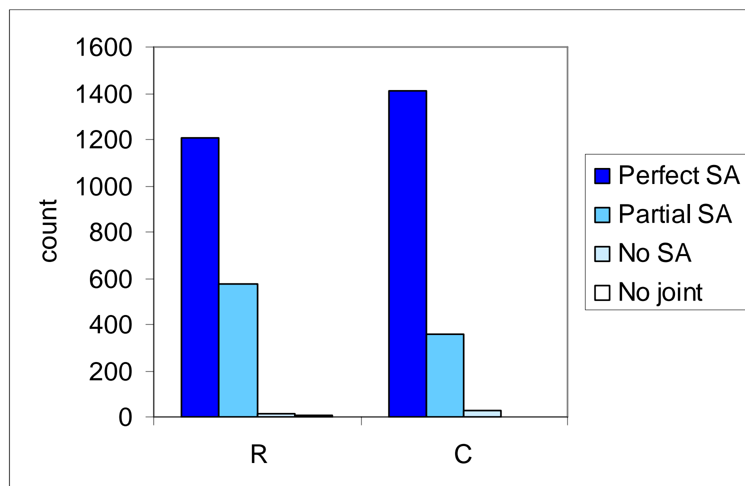
The 0201 components are obviously the superior self-aligners. Figure 20: compares the package sizes for the resistors only, and shows the results for the capacitors. Note that when only the capacitors are compared, the 0603 components are a match for the 0402 components; apparently, the 0603 components' poor score is attributed primarily to the resistors.

Figure 10: Comparison of package sizes – capacitors only



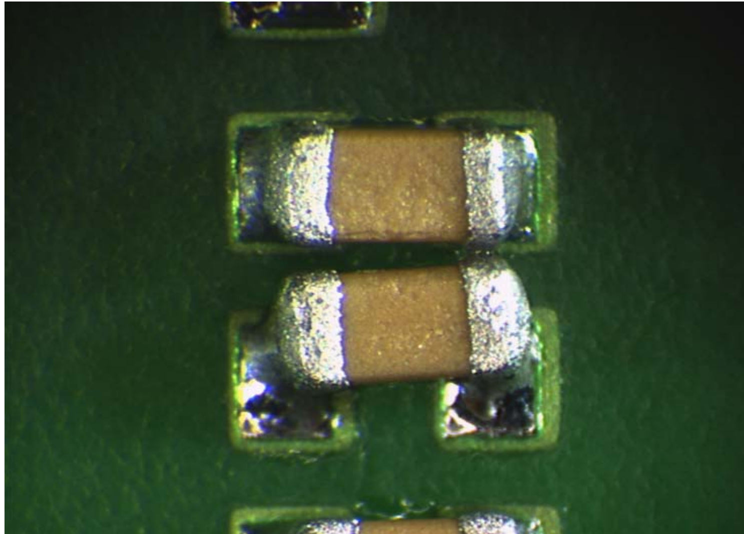
Reversing the plots, appears to show that the capacitors are better self-aligners than the resistors. For the 0201 components, however, no difference is seen between the packages (nearly all achieve perfect self-alignment), and for the 0402 components the resistors appear to self-align a little better. Thus, the higher "perfect self-alignment" bar for the capacitors in is mostly due to the 0603 components, where the capacitors self-align far better than the resistors, as can be seen from a comparison of and .

Figure 11: Comparison of resistors and capacitors



Finally, what became of the 0603 and 0402 components that were reflowed after having been placed such that they made contact? All of the pairs of 0402 components separated, and only two pairs of 0603 components ended up soldered together at one end.

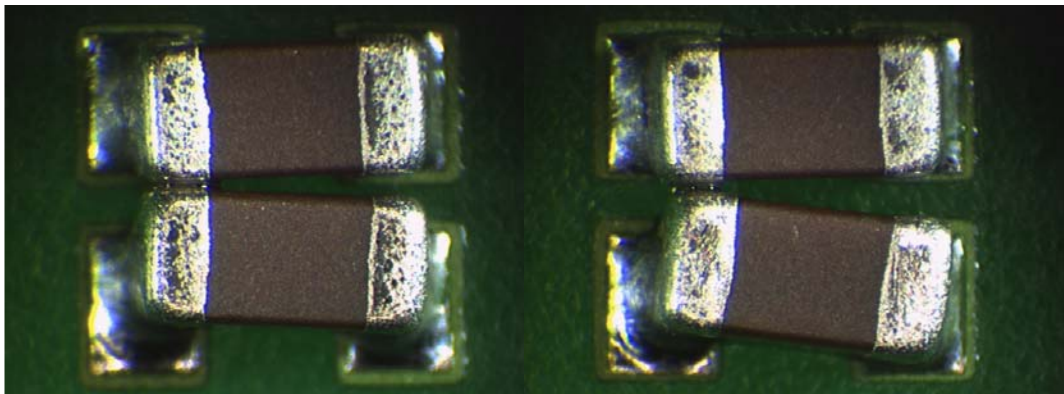
Figure 23: 0402 components with a flux connection



A droplet of flux connected one of the pairs of 0402 components, but this is not considered to be a defect. Some solder paste was accidentally squeezed in between a pair of 0402 components while they were manipulated. This pair formed a short circuit after reflow, but is excluded from the results. Thus, a total of 119 pairs of 0402 components, or 238 connections, were soldered this way, and none gave rise to defects.

The two instances in which short circuits were found with the 0603 components are shown in .

Figure 12: Short crcuits between 0603 components



Discussion

Alpha Run

Zero defects were found with respect to the 0201 assembly, in the alpha run. This translates to a defect level of less than 55 ppm, with a 95 % confidence level. Thus, incorporating 0201 components into the defined platform should not present any serious problems.

Tombstoning

Although not enough components were soldered for a solid statistical foundation, it appears as though tombstoning of 0201 components is not likely to bring down the entire process. Due to the robustness of the process, and the ensuing zero defects, it is unfortunately not possible to compare the 0201 components' inclination to tombstoning to that of its larger brothers, 0402 and 0603; likewise, it is impossible to compare resistors and capacitors, or the effect of the μvia.

Self-Alignment

The 0201 components turned out to be very good self-aligners. Even at an offset of 50 % in the y direction, the vast majority was pulled completely onto the solder lands. However, the four components that did not form a joint at one side may be a cause for concern.

Comparing the three package sizes shows that the components appear to be better at self-aligning as they become progressively smaller. The smaller components have a lower mass, and thus a smaller force of static friction that keeps them in place by resisting the force from the surface tension. Furthermore, they rest on a smaller surface area, so that the contact with the solder resist layer – which could have irregularities that prevent motion – is smaller than for the larger packages. On the other hand, the solder meniscus pulls on a shorter length of component metallisation, so that the force drawing the components to the solder lands is also smaller. Overall, it looks like the lowering of the frictional forces wins.

The 0201 components are all such good self-aligners that it is impossible to compare the various parameter settings. With the 0402 components, however, the resistors are the better self-aligners, whereas for the 0603 components this is the case for the capacitors. This difference is thought to be due to variations among batches of components. Irregularities on the component metallisations, such as a small burr, are likely to disturb the balance between the forces by preventing any movement at all. It may well be that the 0402 capacitors happened to be less smooth than the resistors, and vice-versa for the 0603 components.

Finally, the self-aligning forces that draw neighbouring components that make contact after placement apart, toward their own solder lands, appear to be quite successful. All of the pairs of 0402 components were separated, and only two of the 120 pairs of 0603 components were not separated. Note that the situation created in this experiment is extreme: in production it is very unlikely that two neighbouring components could ever be placed at such totally opposing offsets (one in the positive, the other in the negative y direction). Furthermore, once one of these components is placed it would be very difficult for the nozzle placing the second component to come down and release the component so that it makes contact with its neighbours at both ends. Nonetheless, the occupied areas are apparently designed with such a safety margin that few defects occur even in this extreme case, for 0402 and 0603 components, that is.

As the smaller 0201 components show even better self-aligning properties than the larger packages, they would be expected to be even more successful at separating during reflow. Unfortunately, the experiment could not be done with 0201 components themselves. Recall, however, that many defects were seen with the 0201 components when the occupied area was disregarded (Chapter 0). As the components are expected to be separated when their metallisations touch after placement, the problem when the occupied area is disregarded is likely to lie in contact between the solder paste deposits.

Conclusions

- Zero defects were found out of 27,164 mounted components (54,328 soldered connections), which translates to a defect level of less than 55 ppm (at a 95% confidence level).
- With respect to sensitivity to tombstoning, no conclusion can be drawn on the 0201 components compared to the larger 0402s and 0603s, or as a function of other parameters, as no tombstoning was seen at all. Note that this does *not* suggest that 0201s are not prone to tombstoning.
- The 0201 components are more successful at self-aligning than the larger 0402 and 0603 packages, which suggests that placement is not as critical as would be expected regarding their size.