What Do You Want on Your Tombstone?

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ABSTRACT

Tombstoning, draw-bridging, bill-boarding, and skewing are all common defects that are caused by movement of components out of their intended position. This is reminiscent of pepperoni lifting up while baking a Tombstone pizza. These defects typically occur with passive components (e.g. 1206, 0805, 0603 Imperial components) and are a common issue for electronics manufacturers. Tombstoning, draw-bridging, bill-boarding and skewing can be caused by the circuit board design, pick and place errors, stencil design, reflow profile, and other potential sources. These potential causes of tombstoning and related defects were studied in order to create solutions for this issue. This paper summarizes the results of this work.

Circuit board design can create the potential for tombstoning. One example of this is when the PCB design utilizes one pad set for multiple component sizes such as 0805 and 0603 Imperial components. These pad sets may be too close together for the larger passive components, but also too far apart for the smaller components. Another example is when the pad at one end of the component sits on a ground plane which acts as a heat sink during reflow. The other end of the component sits on a standard copper defined pad. During reflow, there is a temperature differential between these pads which causes the solder paste on the standard copper defined pad to melt first. This can lift or skew the component before the solder paste on the ground plane pad melts.

The stencil design is often based on the copper pad layout rather than the component lead layout. When the pad set is farther apart than the component leads, the solder paste is printed off target with respect to the actual component leads. If the component leads sit to the inside of the solder paste bricks, then tombstoning or draw-bridging can occur. If the component leads sit outside of the center of the solder paste bricks, then skewing and mid-chip beading can occur. Proper alignment of the component into the solder paste bricks is necessary to mitigate these issues. A modified stencil design based on both the circuit board pad layout and the component layout can be used to solve tombstoning, draw-bridging, bill-boarding and skewing issues.

Use of an anti-tombstoning solder paste can also help reduce the potential for these issues. Anti-tombstoning solder pastes typically employ solder alloys which melt in a wide range thereby allowing the solder paste bricks at both ends of the component to melt at the same time which reduces the potential for tombstoning. Adding a longer soak to the reflow profile can also help with this issue. Soak profiles help to equalize temperature differences from one pad to another thereby helping the solder paste bricks to melt at the same time at both ends of the component. All of these variables are studied in this work and solutions for tombstoning are presented with respect to their effectiveness.

Key words: tombstone, draw-bridge, skew, stencil design, pad design, reflow profile, soak profile.

INTRODUCTION

Tombstoning, draw-bridging, bill-boarding, and skewing are defects that have been around for many years (Figure 1).

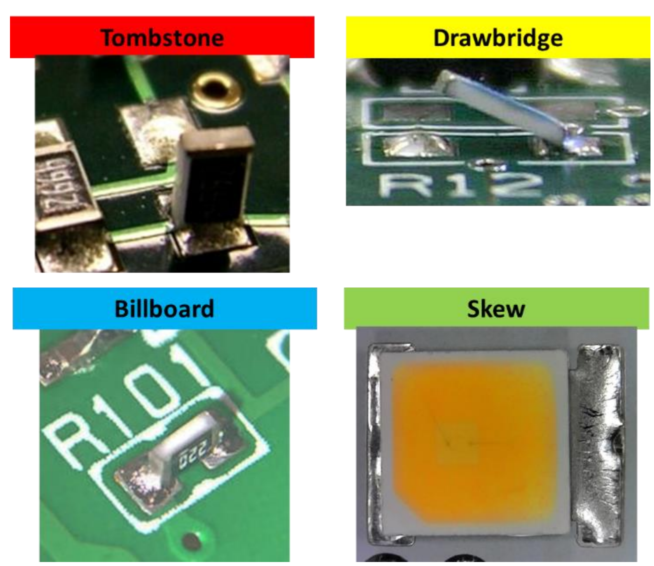

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Figure 1. Examples of tombstone, drawbridge, billboard, and skew defects.

Tombstoning is a condition where a component lifts up at one end, loses contact with a solder joint, and stands near vertically on one of the solder connections. A drawbridge is similar to a tombstone where the component lifts on one end and loses contact with a solder joint, but the component ends in a less than vertical position. Both tombstoning and draw-bridging result in an open electrical connection. Billboarding is a defect where a component flips up on one side but still has contact to the solder joints, and would likely pass electrical testing. Skew is a condition where a component shifts on the solder joints which can lead to open or shorted connections to the solder joints. The commonality of each of these defects is that the component is not in the intended position on the circuit board.

Tombstoning and associated defects have many potential causes. The location of the solder paste print and the component placement can have a dramatic effect on these defects. When the solder paste is unintentionally printed "off-target" with respect to either the component or the board pads, then normal self-correction of the solder during reflow will move the component. If the component is placed "off-target" with respect to the solder paste then it will again move during reflow. The location of the printed solder paste and the component placement can be "off-target" due to the board design, component design, or due to simple alignment errors in these processes.

Thermal differences from pad to pad on the circuit board can cause tombstoning and related defects. Passive chip components, bottom terminated components (BTC's), and other components have ground plane connections and input/output (I/O) connections to the circuit board. During reflow, the ground plane connections heat up more slowly than I/O connections due to heat sinking. This causes a difference in the time of melting between the solder connections on the component. If the solder at one end of the component melts before the other, then the force of coalescence and wetting of the solder may move the component.

Stencil design, solder paste formulation and alloy, and reflow profile can all have an effect on tombstoning and related defects. It is important to look at the circuit board design and the component layout when designing the stencil for solder paste printing. It is also important to choose a solder paste that is less susceptible to tombstoning like "anti-tombstoning" solder pastes. Lastly, it is important to use the recommended reflow profile for the solder paste in an effort to minimize tombstoning. This paper summarizes work done to test these variables and the effects on tombstoning and related defects.

PRIOR WORK

P. Neathway, et. al., [1-2] conducted detailed studies of tombstoning with 0201 sized components. These studies included varying component type, pad designs, stencil designs, component placement, solder paste, surface finish, and others. Here is a brief summary of the results.

- Component positional defects (shifting, skewing) were much more prevalent than tombstones.
- Non-wetting was the 2nd most prevalent defect type, where the solder did not fully wet one or both terminations.
- Tombstoning was heavily influenced by placement offsets which simulated errors in placement.
- 0201 capacitors gave many more defects than 0201 resistors. The component lead sizes are smaller for the capacitors and they are 25% taller than the resistors.
- Pad sets with smaller footprints gave more positional defects.
- Some solder pastes created a high rate of positional defects while others created very few defects.
- ENIG surface finish gave 40% more positional defects than OSP surface finish.
- Reflow in air lead to more overall defects, especially positional errors and solder balls (mid-chip beads).
- Reflow in nitrogen reduced most defects but increased the occurrence of tombstoning.

The overall summary of this work is that skew and shift were more prevalent than tombstoning. Positional defects are heavily influenced by pad and component geometry, solder paste print geometry, and component placement. Solder paste formula and surface finish influence wetting speed and solder spread which affect positional defects.

R. Ghaffarian, et. al, [3] studied several different variables with respect to assembly using 0201 components and detailed the resulting defects. Stencil design, surface finish, and solder pastes were varied including an anti-tombstoning solder paste. Lack of significant tombstoning was observed for most of the surface finish - solder paste combinations. Solder beading was the prevalent defect.

Y. Liu, et. al., [4] studied process development for assembly of 01005 components. Pad size, via-in-pad designs, component orientation, component spacing, reflow profiles, and solder mask misalignment were studied. Bridging and tombstoning were the primary defects. Via-in-pad designs had a much higher incidence of tombstones than pads without vias. The tombstone rate was much lower for ramp to peak profile than for the soak profile, which is counter-intuitive.

C. Ashmore [5] studied the criteria for printing solder paste and stencil design for lead-free assembly. Many different components and stencil aperture designs were tested. Capacitors produced 80% of the defects while resistors accounted for only 20% of the defects. 0201 and 0402 packages have a relatively large height to width ratio. This results in greater solder wetting forces pulling on the ends of the components than on the bottom of the components. This is aggravated by misalignment of the printed solder paste, which can lead to tombstoning, draw-bridging and the like.

J. He, et. al, [6] studied self-alignment (during reflow) of smaller passive components. The results are summarized below.

- Misalignment of smaller passive components (R0402M) is worse than that of larger components.
- Self-alignment is superior in the length direction than the width direction.
- The relatively low volume of solder paste used for smaller passive components gives less ability for self-alignment, than for larger components.

Self-alignment of components during reflow can help to correct the position of the components which is especially critical for smaller passives. This is important to minimize the potential for tombstoning type defects.

G. Smith [7] presented methodologies for improving SMT yields through stencil design. A “reverse U-shape” is suggested to remove solder paste from the outside edges of passive components. This has been shown to minimize tombstoning in production environments.

H. Bell et. al., [8] studied reflow defects with lead-free soldering. This paper reported that use of a nitrogen atmosphere and other oven parameters had a significant influence on tombstoning. High soldering speeds cause more tombstoning than lower speeds. Nitrogen atmospheres improve wetting and flow of solder and increased the occurrence of tombstoning.

The major factors affecting tombstoning and related defects presented in this prior work are summarized here.

- Component size and type.
- Component placement offset or placement error.
- Printed circuit board (PCB) pad geometry and position relative to the component leads.
- Solder paste volume and position relative to the component and PCB pads.
- Solder paste type and solder alloy.
- Reflow atmosphere and reflow profile.

EXPERIMENTAL METHODOLOGY

The goal of this work was to test various factors that may influence tombstoning of passive components as well as shifting or skew of other bottom terminated components (BTC’s). The factors which were tested are as follows:

- Pad sets at normal spacing compared to shifted out spacing
- Stencil design including standard rectangular print versus “reverse U-shape” print
- Solder alloy: SAC305, SN100CV, and an Anti-tombstoning alloy mixture.
- Reflow profile: linear ramp to peak as compared to a soak type profile.

A tombstoning test PCB was designed which is shown below (Figure 1).

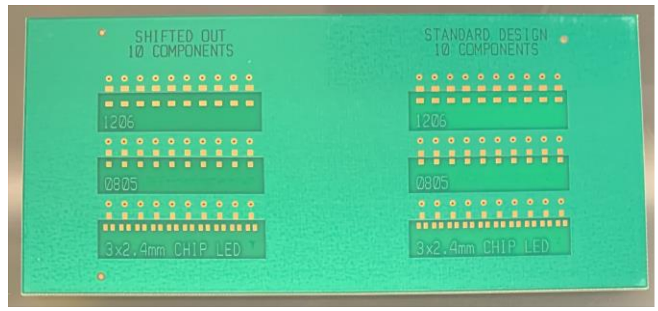

Figure 1. Tombstoning Test PCB.

This tombstoning test PCB was made with 2 oz copper on 0.059” thick FR4 material. The bottom of the circuit board was covered in a large copper ground plane, and the top layer was connected to the bottom layer through a series of plated through via holes. The components used were imperial 1206 and 0805 components and 3 mm x 2.4 mm LED BTC’s. These components were chosen over smaller passives, due to customer reports of tombstoning issues with larger passives.

20 of each component were placed on the test circuit board. 10 of each component used a pad set that was standard for the component size, and 10 of each component used pad sets that were shifted out away from the center of the components. This was done to simulate the use of a larger pad set than standard for each component. Shifting the pad sets away from the component leads was done in an effort to encourage tombstoning.

The pads to pad spacing for each component type and pad set is shown below (Figure 2).

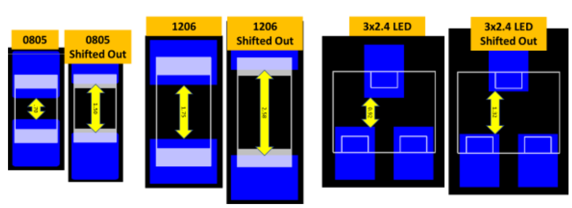

Figure 2. Pad to pad spacing. All values are in mm.

The individual pad dimensions (length and width) were kept the same for the normal and shifted out pad sets for each component. One pad for each component was solder mask defined on the ground plane and the other pad(s) were standard copper defined and were not connected to the ground plane. This was done in an effort to create a thermal difference from one end of the components to the other, in order to facilitate tombstoning.

Several stencils were designed for this test. One was a standard design for these components and the other was a modified “reverse U-shape” design. The standard stencil design is shown below (Figure 3).

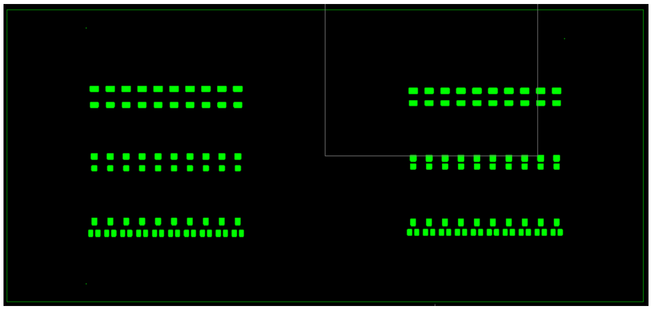

Figure 3. Standard Stencil Design.

The solder paste print of the standard stencil was a standard rectangular pattern with a 25 micron pullback from each edge of the pads. This stencil design provided 93% area of coverage of solder paste on the pads. A modified version of this stencil was made which included 143% area of coverage of solder paste overprinted on the pads.

The “reverse U-shape” stencil design removed solder paste from the outside edges of the pads giving 80% area of coverage of solder paste on the pads. The “reverse U-shape” stencil design is shown below (Figure 4).

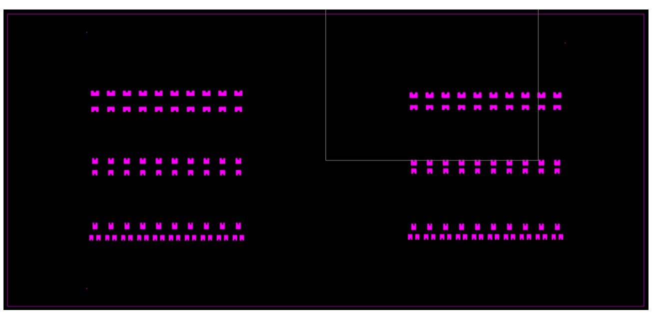

Figure 4. Reverse U-Shape Stencil Design.

A brief explanation of the reverse U-shape stencil design is shown below (Figure 5).

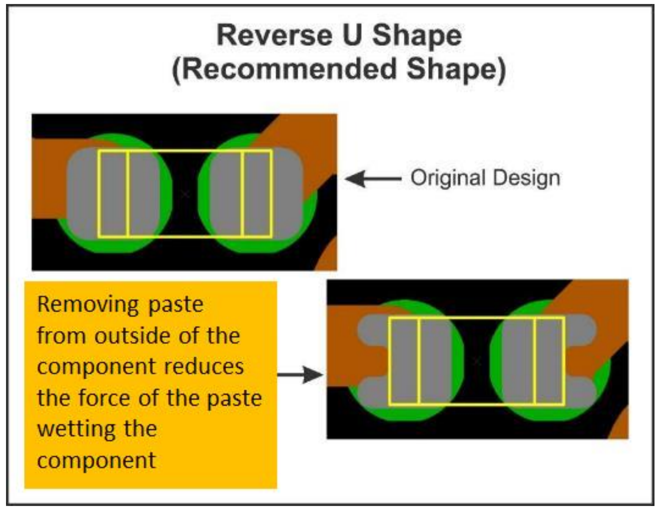

Figure 5. Explanation of the Reverse U-Shape Stencil Design.

Each stencil was made from laser cut fine grain stainless steel and was 127 microns (5 mils) thick. No nano-coatings were used on these stencils.

The solder pastes used were commercially available no-clean lead-free (ROL0) solder pastes. Two different solder alloys were used including SAC305 and SN100CV (Sn/1.5Bi/0.7Cu/Ni) alloys in an IPC Type 4 particle size.

The reflow profiles set up for this experiment are detailed below (Figure 6).

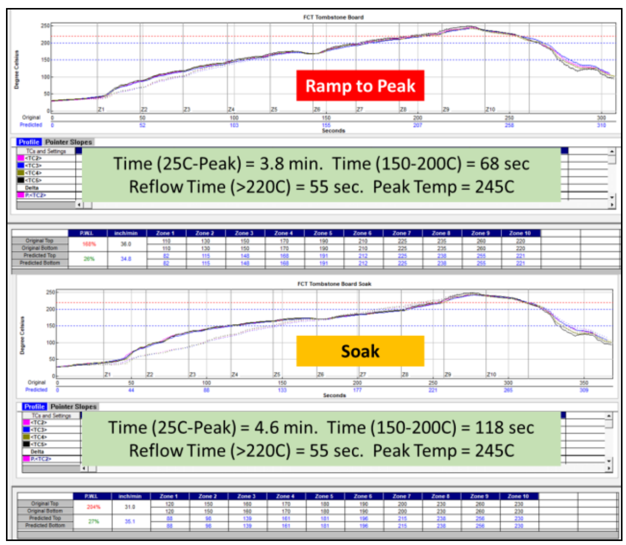

Figure 6. Ramp to Peak and Soak Profiles.

The ramp to peak profile was relatively short with a fast ramp rate in order to promote temperature differentials between the pads on the ground plane and the isolated pads. The soak profile was designed to minimize these temperature differentials.

The process details for this testing are as follows. 5 PCBs were run for each test iteration, with 20 components of each type for a total of 100 opportunities for tombstoning per component, or a total of 300 opportunities per iteration. The following test iterations were run:

A. Standard stencil, SAC305 solder paste, ramp to peak profile.
B. Reverse U-shape stencil, SAC305 solder paste, ramp to peak profile.
C. Standard stencil, SN100CV solder paste, ramp to peak profile.
D. Standard stencil +50% overprint, SN100CV solder paste, ramp to peak profile.
E. Standard stencil +50% overprint, SN100CV solder paste, ramp to peak profile, 0805 components placed onto 1206 pads.

Testing iterations were stopped at this point due to the lack of tombstoning on the test boards. Shifting and skewing were observed and the results are detailed below.

RESULTS AND DISCUSSION

Experimental Work

The defects that were produced were components out of position after reflow including skewing and shifting. In most cases the shifting was in the length-wise direction of the components and many of the components were not touching one of the pads. Tombstoning was not observed in these tests. Some of the defects were caused by placement errors which were not accounted for in this work.

The defects observed were outside of IPC J-STD-001H limits [9] for either maximum side overhang or minimum end overlap. The maximum side overhang limit is 50% for Class 1 and 2 products and 25% for Class 3. The minimum end overlap is 50% for Class 2 products, and 75% for Class 3 products. The defect rates in terms of percentage of components showing these defects out of the total placed are shown below (Table 1).

Table 1. Defect Rates by Test Iteration, Component and Pad Set. SO = Shifted Out Pads, STD = Standard Pads.

Iteration	1206 SO	1206 STD	0805 SO	0805 STD
A	6%	0	38%	0
B	4%	0	80%	0
C	10%	0	58%	0
D	4%	0	40%	0
E	N/A	N/A	62%*	N/A

* Iteration E was run with 0805 components placed onto the standard 1206 pad sets.

The LED components did not produce any defects, and neither did the components placed on the standard pad sets. The shifted-out pad sets produced mostly shifted and skewed component defects with the 0805 components (Figure 7).

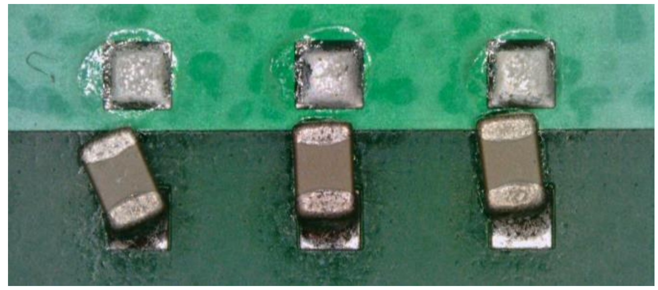

Figure 7. Shifted and Skewed 0805 Components.

The 1206 components on the shifted-out pad sets showed very few defects by comparison to the 0805 components, but the defects that were observed were components shifted off pad. The highest defect rate for the 1206 components was with iteration C, which was the standard stencil design, SN100CV solder paste and the ramp to peak profile. This is the combination that was expected to create higher defect rates.

The highest defect rates for the 0805 components were with iterations B and C. As previously mentioned, iteration C was expected to create higher defect rates. Iteration B used the reverse U-shape stencil design and SAC305 solder paste, which was expected to produce fewer defects. Iteration E included placing 0805 components on 1206 pad sets which were spaced too far apart for the components. The 0805 component bodies barely overlapped the 1206 pads so a high rate of skewing/shifting was expected.

Field Work Case Studies

Field work with tombstoning type defects has been conducted and two case studies are detailed here.

Case Study 1

Shifting was observed with a relatively large bottom terminated LED component (Figure 8).

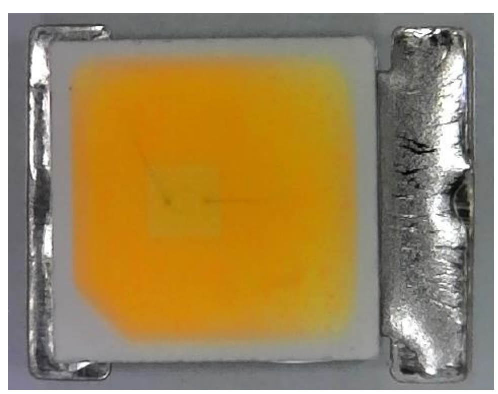

Figure 8. Shifted BTC LED Component.

The solder paste used was a no-clean lead-free solder paste with SN100CV alloy. The defect was occurring on roughly 25 components out of 320 LED placements per panel. Modifying the reflow profile by adding soak time between 150-200°C had little impact on this issue. It is worth noting that the use of the same solder paste with SAC305 alloy showed a much lower rate of this shifting issue.

The PCB pad design had one smaller pad and one larger pad onto which was printed a relatively high volume of solder paste. The component leads were significantly smaller than the PCB pads, and a significant amount of solder paste was printed outside of the component body. When the larger solder paste deposit reflowed, the wetting force was sufficient to float and shift the component out of the intended position, towards the larger pad. A modified stencil was made to reduce the area of the solder paste printed close to 50% and the print was broken up into multiple deposits of solder paste. (Figure 9).

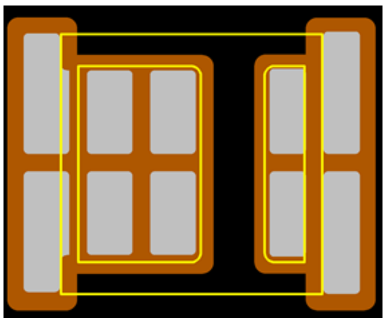

Figure 9. Modified Stencil Design with 50% Area of Coverage.

The shifting was reduced from 25 components per panel to less than 5 components out of 320 placed per panel, which was a substantial improvement. The next change was the use of an Anti-tombstoning solder paste which used a mixture of 90% SN100CV alloy + 10% SAC305 alloy. The melting behavior of this Anti-tombstoning mixture is slowed by comparison to SN100CV alloy alone. This helps the solder paste to maintain a pasty consistency on both pads and equalizes the wetting forces from lead-to-lead on the component. This Anti-tombstoning solder paste along with the modified stencil design resolved the issue.

Case Study 2

Random shifting was reported by another LED lighting manufacturer using a LED component with a 3.0 mm body size. The components shifted far enough to break electrical contact with one of the leads and would not light (Figure 10).

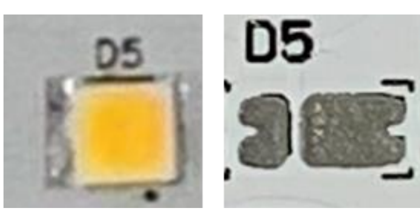

Figure 10. Shifted LED Component Causing an Open Connection and the Solder Paste Print.

This pad layout includes 1 larger pad and 1 smaller pad. The larger pad has a significantly higher volume of solder paste printed onto it than the smaller pad. The shift occurred in the direction of the larger pad. The solder paste used was a no-clean lead-free with SN100CV alloy. It is worth noting that the same solder paste with SAC305 alloy showed a lower rate of this defect.

Modifying the reflow profile by adding soak time between 150-200°C gave a slight reduction in this issue, but did not eliminate the problem. In this case, stencil modifications were not allowed. The next change was testing an Anti-tombstoning solder paste which used a mixture of 90% SN100CV alloy + 10% SAC305 alloy. This Anti-tombstoning solder paste along with the modified reflow profile resolved this issue.

There are many other case studies that could be shared from past experience combating this issue, but the general solutions are the same.

CONCLUSIONS

Tombstoning, draw-bridging, skewing, and shifting are related defects that result in components moving out of their intended position during the SMT process. There are many contributing factors including:

- Pad design
- Stencil design
- Component design
- Placement errors
- Solder paste formula and alloy
- Reflow profile
- Reflow atmosphere

Some components are susceptible to these defects including BTC's like LED's, and smaller passive components. Tombstoning type defects occur due to unequal wetting forces of the molten solder onto the leads of the component. This coupled with temperature differentials from pad to pad and placement errors can lead to defects. These tombstoning related defects can be reworked and do not typically create scrap, but there are costs and production delays associated with this rework.

Process changes that can help to minimize tombstoning type defects include use of anti-tombstoning solder paste, modifying the stencil design, and adding soak time to the reflow profile. In many cases a combination of these changes may be necessary to eliminate these defects.

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