

# Lead-free: Controlling Tombstoning Behavior

TOMBSTONING HAS PLAGUED THE SURFACE MOUNT ASSEMBLY INDUSTRY FOR DECADES. WHILE THE PROBLEM SEEMED UNDER CONTROL, IT HAS BEGUN CREEPING IN AGAIN DUE TO THE MINIATURIZATION OF DISCRETES SUCH AS 0402S AND 0201S. THIS ARTICLE STUDIES TOMBSTONING BEHAVIOR ON A SERIES OF SN AG CU LEAD-FREE SOLDERS AND ATTEMPTS TO FIND A WAY TO CONTROL THE PROBLEM.

By Benlih Huang and Ning-Cheng Lee

The move toward lead-free soldering augments the concern about tombstoning, presumably due to the speculated high-surface tension of lead-free solders. This article studies tombstoning behavior on a series of SnAgCu lead-free solders, attempting to identify a possible “composition window” for controlling the problem. Eutectic SnPb was included as the baseline. Some properties that may be related to tombstoning, such as alloy-surface tension, alloy-melting pattern and solder wetting also were investigated to assess the critical characteristics required to harness this problem.

## Experiment

**Solder Materials** — Several SnAgCu alloys were tested, including 98.3Sn0.96Ag0.74Cu, 97.5Sn2.0Ag0.5Cu, 96.7Sn2.5Ag0.8Cu, 96.5Sn3.0Ag0.5Cu, 95.5Sn3.5Ag1.0Cu and 95.5Sn3.8Ag0.7Cu. Also tested was the control 63Sn37Pb. For each SnAgCu alloy, a solder paste composed of 89% solder powder and a no-clean rosin-based flux was made. The same flux also was used to make SnPb solder paste with 90% metal content. All solder powder used in this study exhibits a particle size of 25 to 45  $\mu\text{m}$ .

**Tombstoning Test** — A 20- x 15.2-cm tombstoning board with Cu metallization was used for tombstoning tests. In each test, 169 of 0402 chips were placed on each test board for each paste, with equal amount of parts being placed on the same board for another paste.

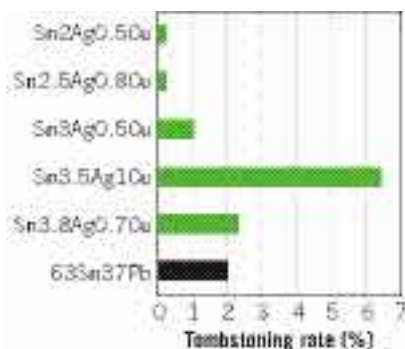
A vapor phase reflow oven\* was used for tombstoning evaluation of the pastes. A vapor phase reflow fluid\*\* with a boiling point of 260°C was used for the SnAgCu pastes and a fluid\*\*\* with a boiling point of 215°C was used for the SnPb paste. For each target paste, eight boards were reflowed. There were 1,352 chips total soldered for each paste.

**Wetting Force and Wetting Time of Liquid Solder** — Wetting force and wetting time also were considered important in determining the tombstoning performance of a solder paste. In this study, a wetting balance\*\*\*\* was used to measure wetting forces and wetting times of solders on Cu coupons using the same no-clean flux that was used for manufac-

turing solder pastes. The experimental procedure followed the IPC-TM-650 with corrected buoyancy. In this test, dip speed was 2 cm/sec, height was 2.5 cm and the time limit was set at four seconds. The solder pot was maintained at 245°C for the SnPb alloy and 260°C for SnAgCu alloys.

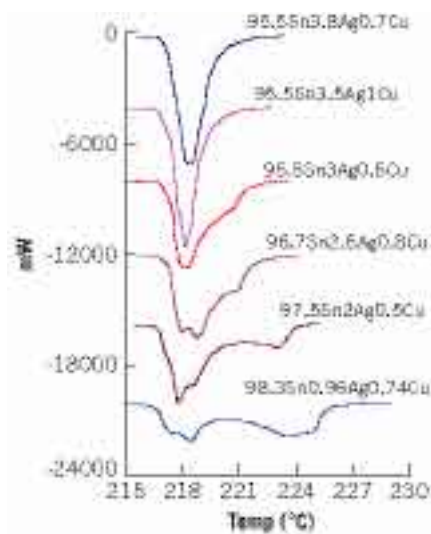
**Differential Scanning Calorimetry** — It was established that the melting behavior of the solder alloys had an impact on the tombstoning performance of the solder pastes. Modifications on melting behaviors of solder alloys have been used to reduce the tombstoning in electronics manufacturing.<sup>1-5</sup> Therefore, it is important to evaluate the melting of target solder alloys using differential scanning calorimetry (DSC). In the present study, an oven\* with a heating rate of 5°C/min. and nitrogen purge was used. Solder powder was used as specimen, as received.

**Surface-tension Test** — The tombstoning performance of solder pastes has been speculated to be related to the surface tension of respective solder alloys. In this study, a solder\*\*\* wetting balance was used to measure the surface tension of solder alloys following established conditions. A piece of alumina coupon with a dimension of 2.5 x 0.4 x 0.062 cm was used for the testing. The solder pot was maintained at 245°C for the SnPb alloy and 260°C for SnAgCu alloys. The measured force with respect to time was translated to a graph of force vs. dip



**Figure 1.** Tombstoning rate of solder pastes with vapor phase reflow process. SnAgCu and SnPb pastes were reflowed at 215° and 260°C, respectively.





**Figure 2.** DSC thermographs of SAC alloys.

depth based on dip speed. When the alumina piece immersed into the solder for a certain depth where the meniscus became stable, the measured force was proportional to the displaced volume of solder. This force may be described as follows:

$$F = L \gamma + \rho g h A.$$

$L$  was the circumference of the alumina piece.  $\gamma$  was the surface tension,  $\rho$  was the density of the solder alloy and  $h$  was the dip depth.  $A$  was the cross-sectional area of the displaced volume. In this force vs. dip-depth graph, as the  $h$  was extrapolated to zero, the  $F = L \gamma$ , thus the surface tension  $\rho$  was obtained. In the present work, the surface tension of the 63Sn37Pb was measured to be  $0.51 \pm 0.01$  N/m, which was consistent with the value of 0.506 obtained in past studies.

## Results

**Tombstoning Test** — Tombstoning test results are illustrated in Figure 1. For lead-free solders, the tombstoning rate is highest for 95.5Sn3.5Ag1Cu, and appears to decrease with increasing deviation in Ag content from 3.5Ag. The defect rate of 63Sn37Pb is slightly lower than that of 95.5Sn3.8Ag0.7Cu. It is interesting to note that reflow temperature has a negligible effect on tombstoning rate of 63Sn37Pb, as evidenced by the 2.00% and 2.24% tombstoning rate observed for 63Sn37Pb when reflowed at 215°C and 260°C, respectively.

**Wetting Force and Wetting Time of Liquid Solder** — No correlation can be established between wetting data and tombstoning

rates. It is stipulated that tombstoning might be correlated with wetting behavior at the incipient solder-paste melting stage instead of wetting at a temperature above the melting point. The relative wetting ability of various alloys may be different significantly for these two conditions; and the unbalanced wetting at the two ends of the chip may be developed already at the onset of the paste-melting stage.

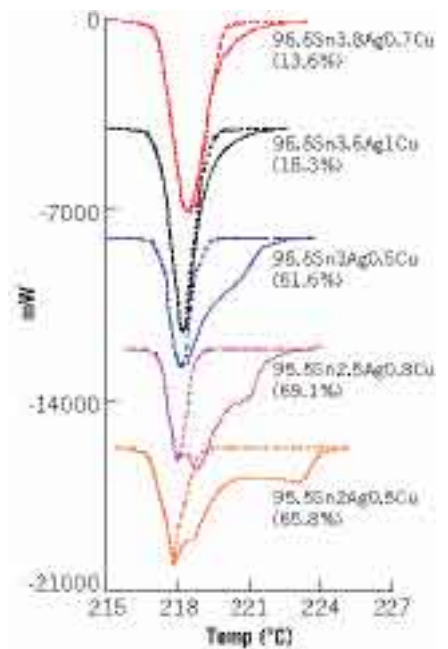
**Differential Scanning Calorimetry** — DSC melting curves of the powder of SnAgCu alloys are shown in Figure 2. The data show that both 95.5Sn3.8Ag0.7Cu and 95.5Sn3.5Ag1Cu exhibit a single melting peak, with the former exhibiting a trace of tail at the high-temperature end. At Ag content below 3.5%, the melting peak broadens up gradually, and double- or multiple-peak endotherm gradually appears with further decrease in Ag content in the SnAgCu alloys.

Tombstoning is expected to occur when solder starts to melt and forms unbalanced wetting to the two component ends. If the wetting occurs at the onset of melting, it is more likely that the mass fraction of solid are at the onset of melting, instead of the pasty temperature range, affecting wetting speed. Hypothetically, a pasty solder with large-mass fraction of solid will exhibit a slow wetting at onset of melting, and consequently will not be able to develop a significantly unbalanced wetting force instantaneously. Accordingly, the greater the mass fraction of the solid at onset of melting, a lower tombstoning rate will be expected.

The mass fraction of solid at onset of melting was estimated by analyzing the DSC thermogram. The following approximations were used in this analysis:

- DSC thermogram of a pure element or eutectic material can be represented by a symmetrical endotherm peak when the heating scanning rate is low.
- All materials exhibit comparable specific heat.

Based on these approximations, a symmetrical virtual endotherm can be constructed on the low-temperature end, with the first peak on the left of the DSC endotherm being the peak of the symmetrical endotherm. For instance, the mass fraction of solid of SAC alloys can be calculated by dividing the endotherm into two regions (Figure 3). The region on the left is the mass fraction of liquid solder when reaching melting temperature. The region on the right is the solid fraction at the same temperature.

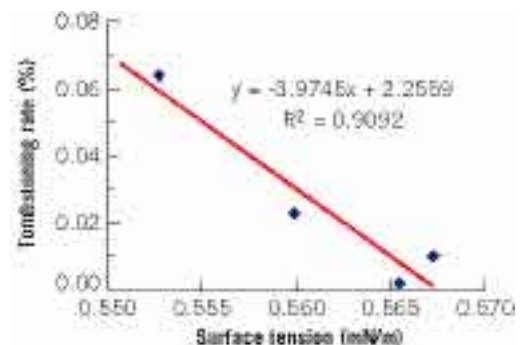


**Figure 3.** Determination of fraction of solid of SAC alloys at onset of melting based on symmetry approximation.

For 95.5Sn3.5Ag1Cu, the area percentage of solid region is 15.3% of the entire endotherm area.

The tombstoning rate decreases with increasing mass fraction of solid at onset of melting. This is consistent with earlier findings that show that the splitting of large, endothermic melting peak was attributed as the cause for the reduced tombstoning frequency for SnPb solders,<sup>1-3</sup> and SnAgX solders<sup>4,5</sup> in reflow soldering.

**Surface Tension** — The surface tension of the SnAgCu alloys was measured using a wetting-balance tester. Within the SnAgCu alloy system, low surface tension correlates with the high tombstoning rate (Figure 4). This high tombstoning rate can be attributed to improved spreading; therefore, improving wetting promised by the low surface tension of liquid solder. It is interesting



**Figure 4.** Relation between surface tension of SnAgCu alloys and tombstoning rate.

to note that 63Sn37Pb exhibits a tombstoning rate comparable with 95.5Sn3.8Ag0.7Cu, regardless of its lower surface tension vs. that of SnAgCu alloy.

Presumably, the fast-wetting driving force for tombstoning caused by low surface tension is offset by the weak pulling force again caused by low surface tension. More work is needed to clear the relationship between surface tension and tombstoning rates when comparing solders with significantly different compositions.

### Conclusion

Effects of solder-alloy composition and properties on tombstoning of SnAgCu have been investigated. Both wetting force and wetting time at a temperature well above the melting point have no correlation with the tombstoning behavior observed at vapor phase soldering. Because tombstoning is caused by an unbalanced wetting force, this unbalanced wetting force may occur at the onset of melting. The DSC study indicates that the tombstoning rate decreases with increasing mass fraction of solid in solder at onset of melting, which is expected to result in a slower wetting speed at the onset of solder melting. This slower wetting in turn results in a more-balanced wetting force, reducing tombstoning. Surface tension also plays a role, as lower surface tension correlates with a higher tombstoning rate. Tombstoning of SnAgCu can be regulated by the solder composition. A maximum tombstoning rate is observed at 95.5Sn3.5Ag1Cu. The tombstoning rate decreases with increasing deviation in Ag content from this composition, particularly toward the end of lower Ag content. SnAgCu composition with an Ag content lower than 3.5%, such as 2.5Ag, is more favorable in terms of reducing tombstoning rates with minimal risk of forming Ag<sub>3</sub>Sn intermetallic platelets. SMT

\* Manix vapor phase reflow oven.

\*\* Solvay Solexis HS-260 vapor phase reflow fluid.

\*\*\* 3M Fluorinert 70 fluid.

\*\*\* Henkel Multicore MUST wetting balance.

### REFERENCES

Article originally published in the 2004 SMTA International Conference Proceedings. For a complete list of references and figures, please contact the authors.

<sup>1</sup> T. Taguchi, R. Katoh, O. Munekata, Y. Toyoda, United States Patent 6,050,480.

<sup>2</sup> Benlih Huang and Ning-Cheng Lee, U.S.

Patent application 09/957,196.

<sup>3</sup> Henkel's Multicore phase reflow technology: [www.multicore.com](http://www.multicore.com).

<sup>4</sup> R. Katoh, O. Munekata, Y. Toyoda, United States Patent 6,554,180.

<sup>5</sup> Benlih Huang and Ning-Cheng Lee, U.S. Patent pending.

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