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Effect of Lead-Free Alloys on Voiding at Microvia

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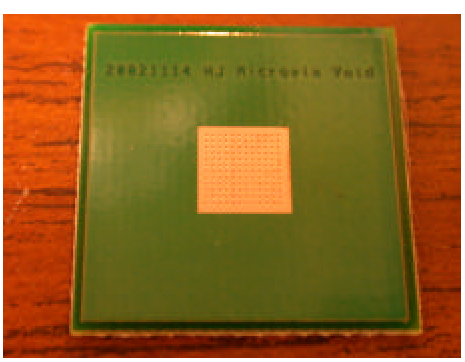
Abstract
For SnAgCu solders, the voiding rate at microvia was studied with the use of simulated microvia, and was the lowest with 95.5Sn3.8Ag0.7Cu and 95.5Sn3.5Ag1Cu. The voiding rate increased with decreasing Ag content from 3.5Ag, mainly due to an increasing surface tension. Voiding at microvia was governed by via filling and exclusion of fluxes. The voiding rate decreased with decreasing surface tension and increasing wetting force which in turn was dictated by the solder wetting or spreading. Both low surface tension and great solder wetting prevented the flux from being entrapped within microvia. A fast wetting speed might also facilitate reducing voiding. However, this factor is considered not as important as the final solder coverage area.

Key words: solder, soldering, lead-free, void, voiding, microvia, surface mount, reflow

Introduction
Voiding in solder joints is a major reliability threat, mainly due to its role as stress concentrator, hence it either initiates crack formation or facilitates the crack propagation, and eventually results in joint failure.[1-4] The problem intensifies with the introduction of microvia and lead-free soldering. The former aggravates the problem by introducing dead corners for adequate solder paste filling and wetting,[5] while the latter worsens the voiding due to its poor solder wetting characteristics.[6,7] Since lead-free soldering is the global trend[8, 9] and microvia technology is here to stay due to its indispensable role in miniaturization,[10] the hope of minimizing voiding, among materials options, resides in the possibility of finding proper lead-free alloys which have less tendency in yielding voids during soldering. In this study, voiding at microvia was studied on a series of SnAgCu solders, with emphasis on finding a possible "composition window" for controlling this problem. Eutectic SnPb was included as the baseline. Properties may be related to voiding such as alloy surface tension, flux chemistry, and solder wetting behavior were also investigated in order to assess the critical characteristics required to harness this problem.

Experimental
Voiding Test
In order to increase the sample size for microvia voiding study, a test was designed so that a large number of microvias were arranged as an area array in a test coupon which was subsequently covered with a thick layer of solder paste. Upon reflow, the solder paste melted and formed a thick layer of molten solder simulating the BGA or CSP solder height. This thick molten solder layer would allow the formation of large voids as those observed in BGA or CSP, as reported in a previous study.[11, 12]

Test Coupon
For effect of alloy composition study, a special simulated microvia coupon was used, with a 12 x 12 matrix of tapered wells on copper with 6 mil diameter (mouth), 4 mil diameter (bottom), 4 mil well depth, and 20 mil pitch. This square matrix of microvia or well was confined by solder mask, as shown in Figure 1(a). Figure 1(b) shows a closed up look of the test coupon.


(a)

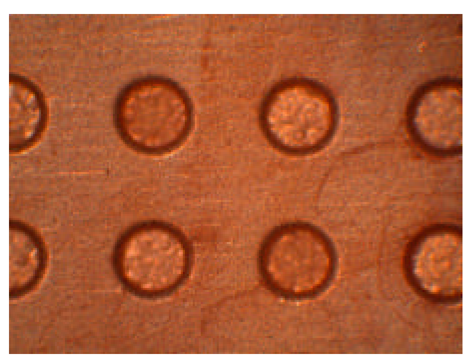

(b)

Figure 1 - Microvia Test Boards Used for Studying Effect of Solder Alloy Composition on Voiding, (a) Overall View of Test Coupon, (b) Closed Up Look of Test Coupon

Figure 2 shows a schematic comparison of a typical microvia and the simulated microvia. Figure 3 shows a schematic view of void formation for each situation. Presence of a thick layer of molten solder on top of simulated microvia allows easy formation of voids due to negligible impact on the curvature of solder dome.[12] This ease of formation of large voids simulates the voiding condition of large solder joints such as that of BGA or CSP.

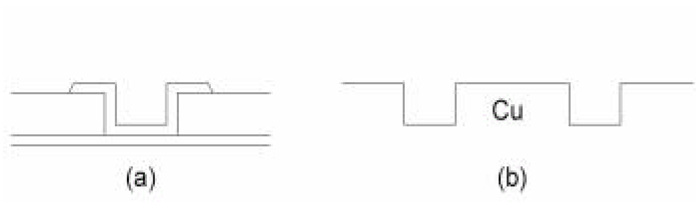


Figure 2 - Schematic of (a) a Typical Microvia and (b) a Simulated Microvia

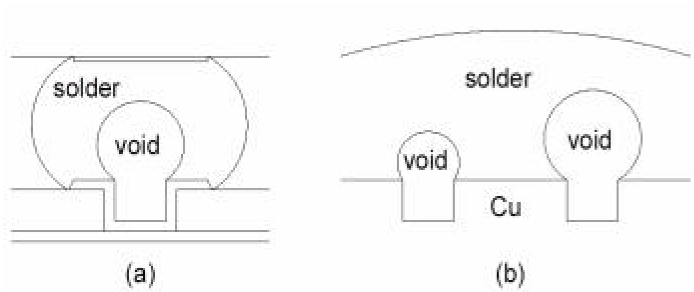


Figure 3 - Schematic of Void Formation at (a) a Typical Microvia, and (b) a Simulated Microvia

Solder Alloy
The alloys used include 95.5Sn3.8Ag0.7Cu, 95.5Sn3.5Ag1Cu, 96.5Sn3Ag0.5Cu, 96.5Sn2.5Ag0.8Cu, and 97.5Sn2Ag0.5Cu. Also included was 63Sn37Pb as control.

Particle Size and Flux Chemistries
Type 3 powder (25-45 microns diameter) was used for all pastes. For each alloy, three solder pastes with 88% metal content were prepared, with the use of two no-clean types N1, N2 and one water wash type W1 flux chemistries.

Processes
<u>Printing</u>
A stencil with a 0.3 inch x 0.3 inch opening and a thickness of 25 mil was used for manually printing paste onto the microvia matrix. Only single print was employed. For each paste, three coupons were prepared.

<u>Reflow</u>
The printed coupons were reflowed under air atmosphere via a BTU convection oven. The profile used for SnAgCu exhibits a peak temperature of 240°C, while that for 63Sn37Pb exhibits a peak temperature of 220°C.

Void Measurement
Void area of solder dome was evaluated using X-ray machine (V.J. Technology) and computer software (PCB Inspector version 4). The average data of three samples for each solder paste was derived. The void content is expressed as area percentage of solder dome. Figure 4 shows x-ray picture of test coupon, while Figure 5 shows a cross-sectional view of voids in a solder dome at simulated microvia.

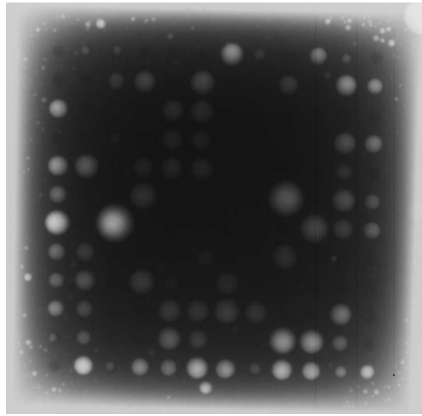


Figure 4 - Example of X-ray Pictures of Test Coupons Using Simulated Microvia and SnAgCu Solder Pastes

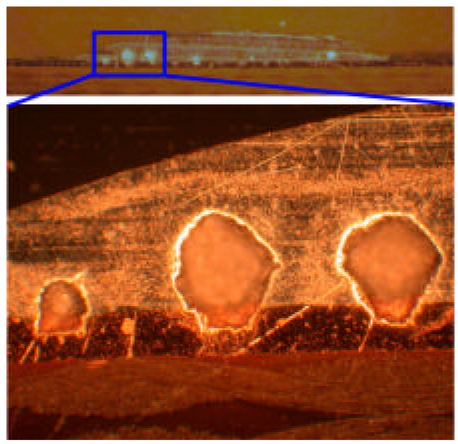


Figure 5 - Cross-Sectional View of Voids at Simulated Microvias in the Solder Dome Formed from SnAgCu Solder Pastes

Wetting Force and Wetting Time of Liquid Solder

The wetting force and wetting time were considered important in determining the voiding performance of a solder paste. In the present study, a Multicore Universal Solderability Tester was employed to measure the wetting forces and wetting times of the solders on the Cu coupons using no clean flux N2 that was used for manufacturing the solder pastes. The experimental procedure followed the IPC-TM-650 with corrected buoyancy. In this test, the dip speed was 2 cm/sec, the height was 2.5 cm, and the time limit was set at 4 seconds. The solder pot was maintained at 245^{o}C for the 63Sn37Pb alloy and 260^{o}C for the SnAgCu alloys.

Surface Tension Test

The voiding performance of solder pastes was speculated to be related to the surface tension of the respective solder alloys. The Muticore Universal Solderability Tester was again used to measure the surface tension of the solder alloys following the conditions established by Miyazki et al.[13] A piece of alumina coupon with a dimension of 2.5 cm x 0.4 cm x 0.062 cm was used for the testing. The solder pot was maintained at 245^{o}C for the 63Sn37Pb alloy and 260^{o}C for the SnAgCu alloys. The dip speed was at 0.5 cm/sec, and the height at 2.5 cm. The measured force with respect to time was translated to a graph of force vs. dip depth based on the dip speed. When the alumina piece was 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. γ was the surface tension, ρ was the density of the solder alloy, h was the dip depth and 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 $F = L\gamma$ and the surface tension γ was thus obtained. In the present work, the surface tension of the 63Sn37Pb was measured to be 0.51± 0.01 N/m, which was consistent with the value of 0.506 obtained by Miyazaki et al.[13]

Results

Effect of Alloy Composition on Voiding

The effect of alloy composition on voiding at microvia is shown in Table 1. For SnAgCu system, as shown in Figure 6, the voiding was found to decrease with increasing Ag content, then level off with further increase in Ag content beyond 3.5Ag. All of SnAgCu alloys exhibit a considerably higher voiding extent than 63Sn37Pb at microvia. This is consistent with the difference in voiding behavior between lead-free solders and eutectic SnPb solder at typical solder joints.[6]

Table 1 - Effect of Solder Composition on Voiding at Microvia

Alloy	Flux	Voiding (area %)	Average
97.5Sn2Ag0.5Cu	N1	32.02	29.94±2.93
	N2	31.22	
	W1	26.59	
96.5Sn2.5Ag0.8Cu	N1	23.44	26.53±2.68
	N2	28.17	
	W1	27.98	
96.5Sn3Ag0.5Cu	N1	17.16	27.33±9.12
	N2	34.77	
	W1	30.05	
95.5Sn3.5Ag1Cu	N1	19.97	22.20±2.68
	N2	25.18	
	W1	21.45	
95.5Sn3.8Ag0.7Cu	N1	17.38	21.83±7.72
	N2	30.74	
	W1	17.37	
63Sn37Pb	N1	2.95	4.98±4.03
	N2	2.37	
	W1	9.63	

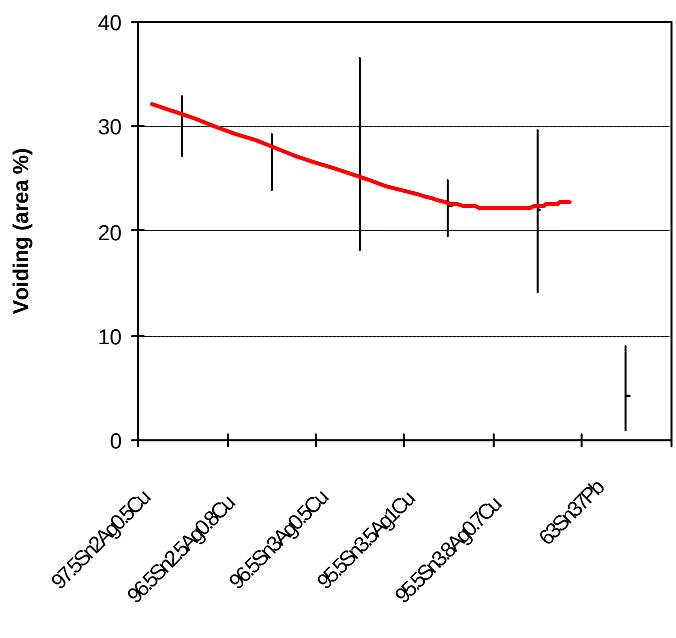


Figure 6 - Effect of Alloy Composition on Voiding at Microvia.

The effect of flux chemistry on voiding does not show a simple result. For SnAgCu alloys, flux N2 appears to be more prone to voiding. On the other hand, flux W1 exhibits the highest voiding rate for 63Sn37Pb. This discrepancy may be caused by the difference in outgassing rate of fluxes at temperature above the solder melting point of the given solder alloy.[14] W1 and N2 may outgas most rigorously at solder molten state for 63Sn37Pb and SnAgCu, respectively.

Wetting Force and Wetting Time of Liquid Solder

The wetting force and wetting time of liquid solders are shown in Figure 7 and Figure 8, respectively. All SnAgCu solders exhibit a comparable wetting force which is considerably lower than that of 63Sn37Pb. On the other hand, all SnAgCu alloys also exhibit a comparable wetting time which is considerably longer than that of 63Sn37Pb.

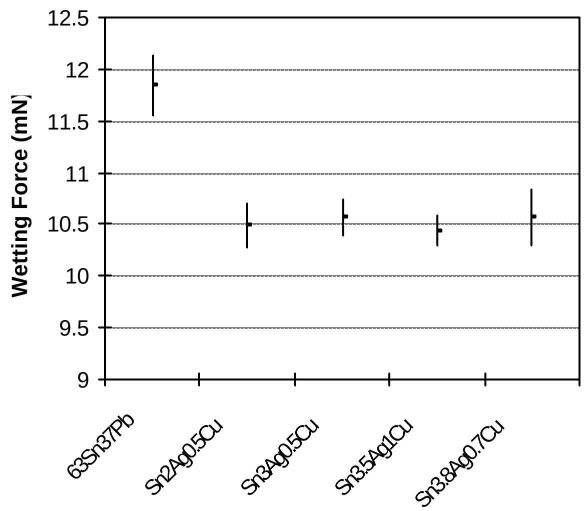


Figure 7 - Wetting Force of 63Sn37Pb and SnAgCu Solders Determined at 245°C and 260°C, Respectively

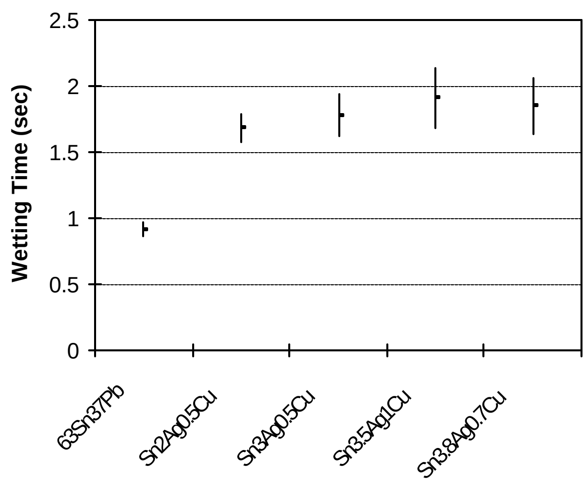


Figure 8 - Wetting Time of 63Sn37Pb and SnAgCu Solder Alloys Determined at 245°C and 260°C, Respectively

In general, a higher wetting force results in a lower voiding rate at microvia, as shown in Figure 9. This higher wetting force reflects a possibly better wetting in this wetting balance test, thus allows less chance to have entrapped flux within the molten solder joints, and consequently results in a lower voiding rate.[15] Since wetting force is a function of both wetting ability and solder surface tension, the effect of wetting force on voiding may also be attributable to surface tension factor, as will be discussed later.

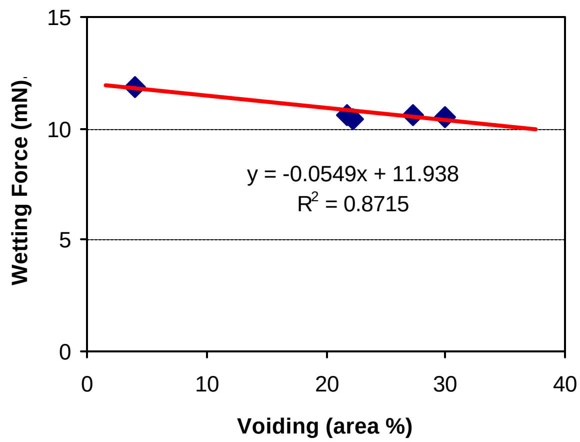


Figure 9 - Relation between Wetting Force and Voiding at Microvia

A shorter wetting time also correlates to a lower voiding rate, as shown in Figure 10. Again, this may be attributed to the better wetting reflected by the shorter wetting time. However, the correlation coefficient, 0.73, is relatively low. Furthermore, the SnAgCu data points exhibit quite some deviation from the trend line. Therefore, it is speculated that the impact of wetting time on voiding may be secondary to some other factors.

This speculation is reasonable in view of the fact that the amount of entrapped flux should be determined by the final solder coverage area or the final wetting state, not the wetting speed. The greater the solder coverage area, the less chance there is for flux to be entrapped.

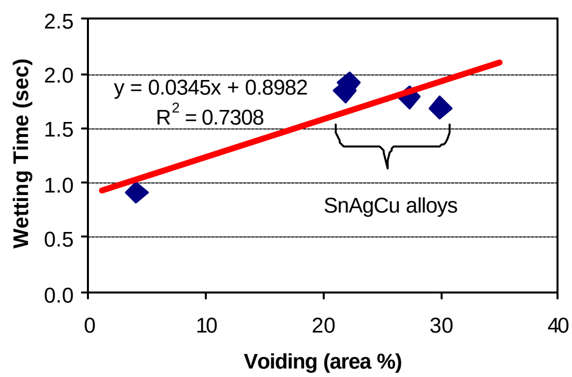


Figure 10 - Relation between Wetting Time and Voiding at Microvia

Surface Tension

The surface tension of the SnAgCu alloys has been measured using a wetting balance, with results shown in Figure 11. The low surface tension correlates very well with the low voiding rate, as shown by the high value in correlation coefficient, 0.9563, in Figure 12. Since a lower solder surface tension favors a greater equilibrium solder spreading,[16] results here are consistent with the speculation that it is the final solder spreading or coverage which governs the voiding rate as discussed above.

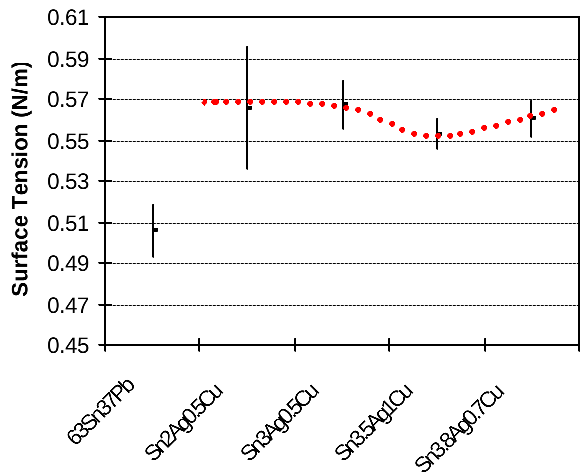


Figure 11 - Surface Tension of 63Sn37Pb and SnAgCu Alloys Determined at 245°C and 260°C, Respectively

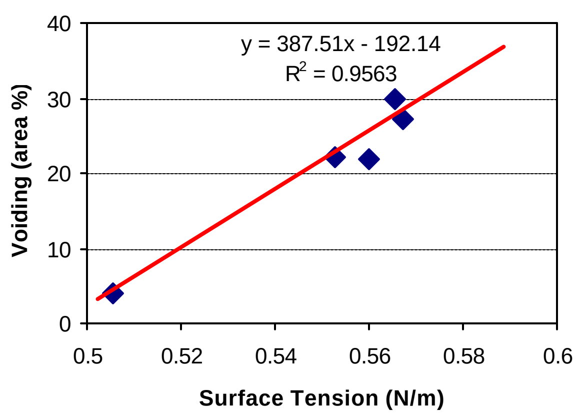


Figure 12 - Relation between Surface Tension and Voiding Rate at MICROVIA for 63Sn37Pb and SnAgCu Alloys

Discussion

In Figure 9, the high wetting force is correlated with low voiding rate, and the high wetting force could possibly be attributed to either high surface tension or high solder wicking along the sample surface. By reviewing both Figure 7 and Figure 11, it becomes clear that the high wetting force is mainly attributed to the high wicking extent. This is made obvious by examining the data point associated with 63Sn37Pb. 63Sn37Pb exhibit the highest wetting force. However, its surface tension turns out to be the lowest one. Accordingly, the primary cause for 63Sn37Pb to exhibit a high wetting force is a greater wicking, which results in a greater downward vector force due to surface tension of solder. In other words, the low voiding associated with the high wetting force is mainly due to the better wicking or spreading of the solder. This better spreading effectively excludes the flux from being entrapped within the interior of the molten solder joint.

Conclusion

For SnAgCu solders, the voiding rate at microvia was studied with the use of simulated microvia, and was the lowest with 95.5Sn3.8Ag0.7Cu and 95.5Sn3.5Ag1Cu. The voiding rate increased with decreasing Ag content from 3.5Ag, mainly due to an increasing surface tension. Voiding at microvia was governed by via filling and exclusion of fluxes. The voiding rate decreased with decreasing surface tension and increasing wetting force which in turn was dictated by the solder wetting or spreading. Both low surface tension and great solder wetting prevented the flux from being entrapped within microvia. A fast wetting speed might also facilitate reducing voiding. However, this factor is considered not as important as the final solder coverage area.

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