As Presented at the IPC/JEDEC 12th Annual Symposium on Lead Free Solders,
March 2006, Santa Clara, CA

PC Board Assembly with Lead Free Hot Air Leveled Solder Coatings

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Introduction

The European Union directives WEEE and RoHS promote recycling and re-use of materials, and ban substances considered health hazards. Similar legislation is being considered in California, China, and other countries. Lead-Free solders have been in use in Japan for several years. Manufacturers planning to sell into the EU market will have to comply with these directives.

In preparation for the July 1, 2006 deadline, numerous RoHS compliant trials have been conducted to examine and evaluate Lead-Free Assembly processes for both solder bar and solder paste. Of prime importance to circuit board assemblers is alloy selection, wetting and wicking capability (through hole fill), process changes and parameters, cost, and demonstrated solderability. Of prime importance to circuit board fabricators is board finish selection, cost, demonstrated solderability, and shelf life.

Lead-Free Alloys For HAL and Assembly

Most studies conducted so far used PCB's with finishes of ENIG, Immersion Silver, Immersion Tin, and OSP. Lead-Free hot air leveled PCBs have been invariably excluded in these investigations. One would almost surmise that Hot Air Leveling (HAL) in the Lead-Free environment is not a viable option. Nothing can be further from the truth.

In the recent past, more than 80% of all PCBs produced worldwide were hot air leveled. Today, still more than 60% of all PCB's produced go through the HAL process. Of all the processes to preserve the solderability of bare PCBs, hot air leveling is still a) the most cost effective, b) the coating that yields the best solderablility of the PCB, c) the coating that produces an excellent shelf life, and d) the coating that produces a product compatible with a wide range of manufacturing processes such as wave soldering, SMT, selective soldering, etc. After all, "nothing solders like solder".

In order for Lead-Free solder to be successful, it should reproduce many of these advantages. A major cost will be the solder. Numerous Lead-Free alloys have been developed. Many of these alloys can be eliminated from consideration for use in HAL and Assembly (Wave Soldering and Solder Paste) for any of the following reasons.
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1) Cost considerations.
2) Material availability of alloy constituents.
3) Compatibility with other solder alloys or soldering processes.
4) Reliability considerations.

The remaining alloys can be placed into one of two major groups.

A) Tin/Silver/Copper alloys
B) Tin/Copper alloys

A.) Tin/Silver/Copper

These alloys contain a minimum of 95% Tin, 1-4% Silver, and 0.1-1% Copper, and are referred to as SAC alloys (**S**n**A**g**C**u). Alloys will vary widely from one solder vendor to the next. However, the IPC Solder Products Value Council tested various SAC alloys in solder paste and determined that "due to lower cost and equivalent performance, the 96.5/3.0/0.5 SAC alloy be the lead free alloy of choice for the electronics industry". It found no significant difference between the alloys in screening, performance, defect rate, metallurgy, or thermal cycling. The alloy melts at 217°C compared to 183^0C for the eutectic tin/lead alloy. A reasonable amount of long term reliability and other data are also available. The recommended operating temperature for SAC305 in both paste and bar ranges from 255^0C to 265^0C.

Advantages of SAC alloys: Readily accepted by industry, lower melt point compared to Sn/Cu alloys.

Disadvantages of SAC alloys: Higher cost, limited longevity studies, dull crystalline and grainy solder joint, joint cracking, solder voids, higher melt point compared to Sn/Pb alloys, stainless steel corrosion potential, and for HAL poor coplanar surfaces.

B.) Tin/Copper

These alloys contain in excess of 99% tin with varying amounts of copper. The generally accepted eutectic composition contains Sn99.3/Cu0.7% with a melting point of 227^0C. However, experience shows that tin/copper alloys by themselves when used in assembly and HAL operations produce boards with dull, grainy, large crystal solder joints and/or surfaces. In the past, such alloys were indicative of poor quality soldering. For this reason, small additions of grain refiners are sometimes added to the base tin/copper alloys to produce bright, shiny boards and solder joints that are not as grainy as SAC alloys. These grain refiners are elements such as cobalt, gallium, germanium, or nickel. An example of this alloy would be the cobalt containing Sn99.5Sn/Cu0.5/Co alloy which melts at 227^0C.

Advantages of Sn/Cu alloys: Lower in cost, binary instead of tertiary alloy.

Disadvantages of Sn/Cu alloys: Limited longevity studies, dull crystalline solder joint in the absence of grain refiners, no longevity studies, higher melt point than SAC and Sn/Pb alloys, stainless steel corrosion potential.

Advantages of Sn/Cu/Co alloy: Lower in cost, binary instead of tertiary alloy, brighter and shinier solder joints and/or surfaces with less graininess, no joint cracking or solder void problems.

Disadvantages of Sn/Cu/Co alloy: Limited longevity studies, higher melt point than SAC and Sn/Pb alloys, stainless steel corrosion potential.

Even though there is a substantial difference of 44^0C between the melting points of tin/copper based alloys and the Sn63/Pb37 alloy, the actual difference in the process temperatures these two alloys are used at, both in assembly and HAL, is only $10\text{-}20^0$C. Tin/lead alloys are usually run at temperatures of $250\text{-}260^0$C, whereas tin/copper/cobalt alloys are operated at temperatures in the range of $260\text{-}270^0$C and SAC305 at $255\text{-}265^0$C in HAL, wave and SMT soldering equipment. The following table details the physical properties for some Lead-Free and tin/lead alloys.

Table 1: Physical Properties

	SAC 305	Sn/Cu/Co	Sn63/Pb37
Melting Point (^{0}C)	217	227	183
Density (g/cm^3)	7.4	7.3	8.4
Operating Temperature (^{0}C)	265	265	245
Tensile Strength (M Pa)	52	28	31
Elongation	27	27	35
Thermal Conductivity (J/m•s •K)	64	64	50
Electrical Resistance (µΩm)	0.15	0.13	0.17
Thermal Shock (-40/+80 ^{0}C Each 1 Hr)	›1000 Cycles	›1000 Cycles	500 Cycles

Cost of Lead-Free alloys (or is LEAD-FREE really FREE?)

Almost all Lead-Free alloys replace the lead with tin. This **almost doubles** their cost. The situation for the SAC alloys is even more substantial. The SAC alloys all contain silver (to lower the melting point). The widely used SAC305 alloy costs **3 times** that of Sn63/Pb37 alloy. So, one can readily see that the conversion to Lead-Free will be any thing but FREE. With the tin/copper based alloys costing 1/3 less than the SAC305 alloy, the obvious choice from a cost point of view for HAL and wave soldering is the tin/copper based alloy. For SMT applications, the alloy choice and cost is not as much a consideration since the cost of solder paste is much more dependent on labor, so SAC305 would seem to be the solder paste of choice.

When choosing a lead free alloy, either binary or tertiary, several considerations should be kept in mind. Firstly, it is much easier to keep a binary alloy in spec compared to a tertiary alloy. Secondly, the 10^0C melting temperature differential means little in a through hole wave soldering application, while that same 10^0C may mean much in a re-flow oven where dwell times are longer. Since both alloys are compatible with all other board finishes, there seems to be little justification to spend the extra money on a silver containing alloy for wave soldering and HAL.

Other Available Board Finishes for PC Fabrication

Various board finishes are available to protect the underlying copper on bare boards. These finishes include Immersion tin, Immersion silver, ENIG, OSP, and Hot Air Leveling solder alloys.

Immersion Tin is process dependent with a relatively high cost. A 6-12 month shelf life is promoted. The thickness is limited to about 1 micron. The coating is porous. This process may lose solderability as the tin diffused into the copper.

Immersion Silver is also process dependent with a relatively high cost. The shelf life is the same as Immersion tin, with tarnished boards being observed after only two or three months. The thickness is limited to less than 1 micron with an average thickness of 0.2 to 0.3 microns, again exhibiting porosity.

ENIG (Electroless Nickel/Immersion Gold) again is process dependent with a relatively high cost due to new equipment and chemicals. The average thickness is between 0.05 to 0.09 microns. This process may introduce gold into the solder joint which may cause a more brittle joint. Process can go awry more often than HAL requiring replacement of chemicals.

OSP (Organic Solder Preservative) has a somewhat limited shelf life. It works better with high activity fluxes and is more dependent upon temperature.

Wetting Balance Tests

It would be expected that the ideal Lead-Free replacement solder, in order to yield results comparable to Sn63/Pb37 tin/lead solder, would wet copper surfaces as good as Sn63/Pb37. Wetting balance tests were conducted on the Sn/Cu/Co alloy to determine if there existed an optimal wetting temperature. The test was used as a means to compare the wetting characteristics of the Sn/Cu/Co alloy to that of the Sn63/Pb37 alloy. Testing was conducted on a Metronelec Wetting Balance.

Wetting balance tests were first conducted at 250°C for Sn63/Pb37 (its recommended operating temperature) to establish a baseline to which the Lead-Free alloy could be compared. Next, wetting balance tests were conducted on the Sn/Cu/Co alloy at temperatures of 250°C, 255°C, 265°C, and 275°C.

a) Sn63/Pb37 alloy

Temperature	250°C
Maximum wetting force	0.32 mN/mm
Time to achieve maximum wetting	0.241 sec
Average force at 1.125 seconds	0.32 mN/mm

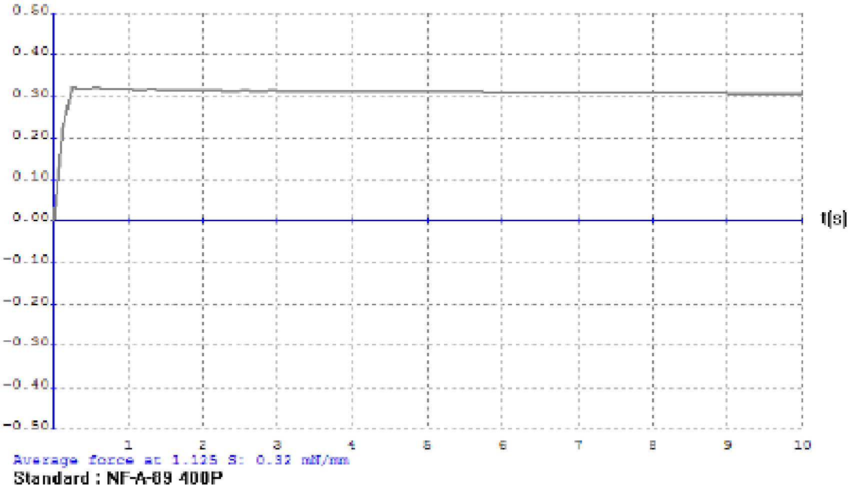

Figure 1: The graph above is the average of 20 tests for baseline group – 63/37 tested at 250°C.

b) Sn/Cu/Co Alloy

Temperature	250°C	255°C	265°	275°C
Maximum wetting force (mN/mm)	~0.30	~0.30	>0.31	>0.31
Time to achieve max. wetting force (sec.)	~0.27	~0.26	~0.24	~0.24
Average force at 1.125 seconds (mN/mm)	0.29	0.30	0.31	0.30

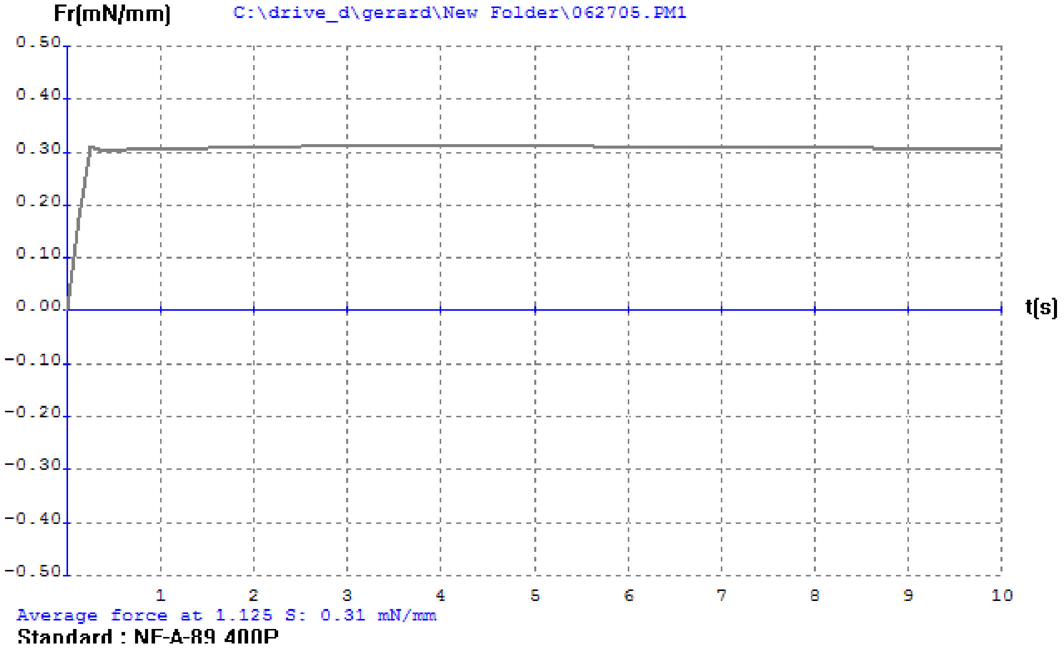

Figure 2: The graph above is the average of twenty tests for 99.7Sn/0.3Cu/Co at 265°C.

Test Results Discussion

Looking at the results with the time scale set to the test time – 10 seconds – there is little to differentiate between the two groups. A statistical examination of the spread shows that Sn63/Pb37 is statistically different to the Lead-Free at all temperatures. *A closer examination of the initial 1-second of wetting, important given the potential 2 seconds of average contact time in HAL and wave soldering, and longer contact time in re-flow, shows the differences between the groups.* In an ideal wetting scenario, the initial rise to maximum wetting should be as steep as possible. The slope of the Sn63/Pb37 is almost uniform in its rise. The Lead-Free at 250°C and 255°C has a slower initial wetting. At 265°C and 275°C the rate of rise more approaches the ideal shape.

For the Sn63/Pb37 solder, wetting was instantaneous, rising to maximum wetting force in 0.241 seconds. Maximum wetting force was 0.32mN.mm of wettable length.
For the Sn/Cu/Co at 265°C, the wetting was also instantaneous. The rate of rise is uniform, near textbook, and the maximum wetting force is very slightly lower at 0.31mN/mm.

For the Sn/Cu/Co at 275°C, the wetting was also instantaneous. The rate of rise is very similar to the Sn63/Pb37 group, and the maximum wetting force is very slightly lower at 0.31mN/mm.

The wetting characteristics for the Sn99.5/Cu0.3/Co can be made to simulate that of Sn63/Pb37 with an increase in the operating temperature of between 15°C to 25°C. Increased preheat in production may be able to help compensate for this required temperature increase, which should help control the dissolution rate of copper. Wetting forces at the increased temperature are also improved to match that of Sn63/Pb37.

Copper Loading Capacity of Solder

There is substantial data available as to how much copper content can be tolerated in a Sn63/Pb37 operation. The existing J-STD-001 shows a maximum copper content of 0.3. Experience gained through years of tin/lead soldering revealed that the performance of solder was adversely affected when the copper content reached approximately 0.5% at operating temperatures of between 250^{0}C and 260^{0}C. Unfortunately, this same data does not yet exist for Lead-Free solder alloys. The eutectic tin/copper alloy of Sn99.3/Cu0.7 already has a copper content greater than what can be tolerated in a tin/lead soldering process.

In an attempt to remedy this lack of data, Metallic Resources, Inc. conducted an experiment to determine if there existed a correlation between its Lead-Free alloy and tin/lead solder with regards to copper concentrations. Pure copper sections of identical shape and weight were introduced into both Sn/Cu/Co and tin/lead molten solder baths at various temperatures. The experimental bath temperatures were selected for the purpose of simulating potential operating temperatures. The copper pieces were immersed in circulating solder baths for 15 minute periods. The copper piece was removed after 15 minutes and a sample was drawn from the solder bath. The solder samples were analyzed on an Emission Spectrophotometer and then returned to the solder bath. The following table summarizes the data thus obtained.

Table 2: Sn63/Pb37 vs. Sn/Cu/Co Copper Dissolution

	63/37 Alloy				Sn/Cu/Co Alloy				
Time (Minutes)	**Temp. 225° C**	**Temp. 250° C**	**Temp. 260° C**	**Temp. 270° C**	**Temp. 255° C**	**Temp. 260° C**	**Temp. 265° C**	**Temp. 270° C**	**Temp. 275° C**
0	0.005%	0.007%	0.007%	0.008%	0.383%	0.466%	0.383%	0.374%	0.397%
15	0.011%	0.016%	0.018%	0.099%	0.465%	0.546%	0.464%	0.449%	0.458%
30	0.013%	0.108%	0.127%	0.159%	0.490%	0.575%	0.548%	0.528%	0.514%
45	0.017%	0.163%	0.168%	0.217%	0.543%	0.627%	0.570%	0.582%	0.587%
60	0.017%	0.194%	0.215%	0.277%	0.534%	0.654%	0.610%	0.658%	0.693%
75	0.018%	0.224%	0.251%	0.314%	0.607%	0.668%	0.646%	0.701%	0.779%
90	0.141%	0.252%	0.279%	0.344%	0.633%	0.693%	0.708%	0.711%	0.826%
105	0.161%	0.275%	0.338%	0.365%	0.655%	0.714%	0.718%	0.741%	0.875%
120	0.174%	0.296%	0.343%	0.403%	0.683%	0.743%	0.751%	0.751%	0.918%
135	0.182%	0.338%	0.391%	0.412%	0.695%	0.761%	0.773%	0.806%	0.946%
150	0.196%	0.367%	0.398%	0.437%	0.703%	0.780%	0.807%	0.844%	0.974%

165	0.195%	0.370%	0.408%	0.455%	[redacted]	0.693%	0.782%	0.809%	0.893%	1.017%
180	0.206%	0.408%	0.445%	0.460%	[redacted]	0.702%	0.787%	0.824%	0.881%	-
195	0.211%	0.402%	0.444%	0.468%	[redacted]	0.707%	0.800%	0.838%	0.887%	-

The above data indicates that the rate that copper is dissolved is a function of both the temperature and the existing copper concentration. The dissolution rate increases as the temperature increases, and the rate decreases as the copper concentration increases. The data for the two alloys' recommended operating temperatures (250°C for Sn63/Pb37 and 265°C for Sn/Cu/Co) is of particular interest. The data points for these two alloys at their recommended operating temperatures were plotted on a graph and then fitted to a logarithmic regression curve.

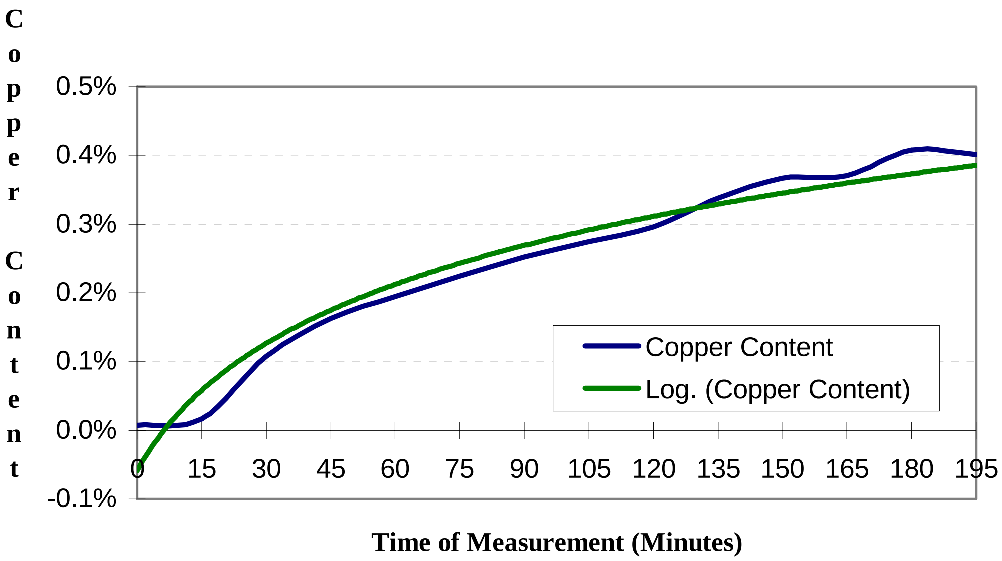

Figure 3: Sn63/Pb37 @ 250°C

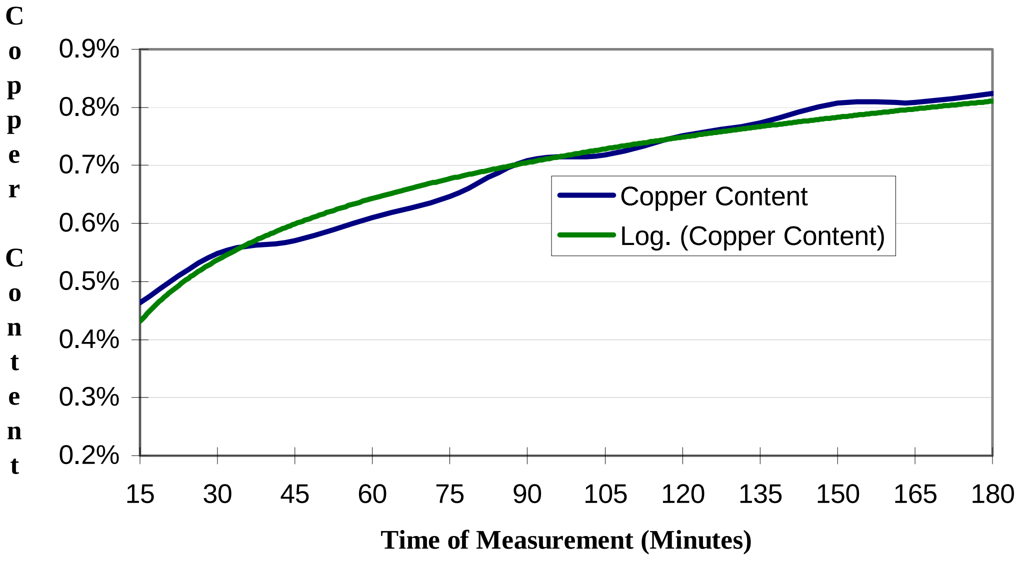

Figure 4: Sn99.5/Cu0.5/Co @ 265°C

Discussion

A review of the Sn63/Pb37 graph shows an initial rapid rise in the dissolution rate to a copper concentration of 0.1% and then a steady rise to a concentration of 0.35% whereupon it levels off to an almost flat rate at 0.40%. Industry experience has shown that performance of the solder begins to deteriorate at around this copper concentration. Very objectionable results are obtained when the solder content reaches 0.5%.

Extrapolating this knowledge to the data obtained for the Sn/Cu/Co alloy, one can expect to obtain satisfactory performance from the solder up to a copper concentration of about 0.85% and expect poor performance above 1.0% when the solder is maintained at an operating temperature of 265°C.

Some other noteworthy observations include that copper is dissolved at a much more slower rate for fresh Sn/Cu/Co with an initial copper concentration of approximately 0.3% than for fresh Sn63/Pb37 with 0% copper across all temperatures studied. Further, both the Lead-free alloy and Sn63/Pb37 were extremely grainy and sluggish close to their saturation points.

Copper thickness reduction

Speculation exists that excessive amounts of copper would be removed from PCBs if hot air leveled with high tin Lead-free solders at higher process temperatures.

To determine whether or not there is reason for concern, a study was conducted wherein PCBs were hot air leveled with multiple passes. As is evident from the following data, there was no difference between the Sn/Cu/Co alloy and 63/37 regarding the amount of copper removed from the PCBs.

Less copper was removed with the Lead-free alloy than with the 63/37 solder after one pass. Also, only 12.5% and 10% was removed after two passes and only 25% and 20% of the copper was after three passes. See data below.

Table 3: Copper Thickness Reduction Data

No. of HAL cycles	Copper thickness (Mils)	
	Sn/Cu/Co	Sn/Pb
0 cycles	0.8 mils	1.0 mils
1 cycle	0.8 mils	0.9 mils
2 cycles	0.7 mils	0.9 mils
3 cycles	0.6 mils	0.8 mils
Cu Thickness Reduction	$\frac{0.8 - 0.6}{0.8} = 25\%$	$\frac{1.0 - 0.8}{1.0} = 20\%$

HAL Coatings - Sn/Cu/Co vs. Sn/Pb

It was mentioned earlier that the percentage of PCBs fabricated with the HAL process is down from a high of 80% of all boards produced to currently only 60%. This reduction as a final PCB finish coincides with the substantial growth in surface mount technology (SMT), which requires flat uniform (coplanar) surfaces. The traditional tin/lead hot air leveling process was unable to provide this segment of the industry with satisfactory coplanar PCBs.

The question to be posed with Lead-Free hot air leveling is: “Are Lead-Free HAL boards better, worse, or the same as tin/lead HAL PCBs with regard to coplanar surfaces?” Initial side-by-side trials have indicated that Sn/Cu/Co has produced slightly thinner, more coplanar coatings than the traditional tin/lead eutectic. These results are constant from study to study. The following are the results for one of these trials from a horizontal hot air leveling machine.

Table 4: HAL Coatings Thickness Data

	63/37 Panels	Sn/Cu/Co Panels
Panels Measured	44	44
Mean	169.6 µ-in.	166.7 µ-in.
Standard Deviation	65.6 µ-in.	49.1 µ-in.

Minimum	109.0 μ-in.	102.0 μ-in.
Maximum	486.7 μ-in.	270.2 μ-in.
Range	377.7 μ-in.	168.2 μ-in

Spread Test Results

Several board finishes, including hot air leveled solder coatings, are available to assemblers. In order to determine how good the new lead free pastes (SAC305 and Sn/Cu/Co) wet, extensive tests were conducted for all available board finishes by screening a known amount of each paste on coupons coated with different board finishes and reflowing them at recommended operating temperatures for SAC305 (255^{0}C) and Sn/Cu/Co (265^{0}C). Results are discussed below.

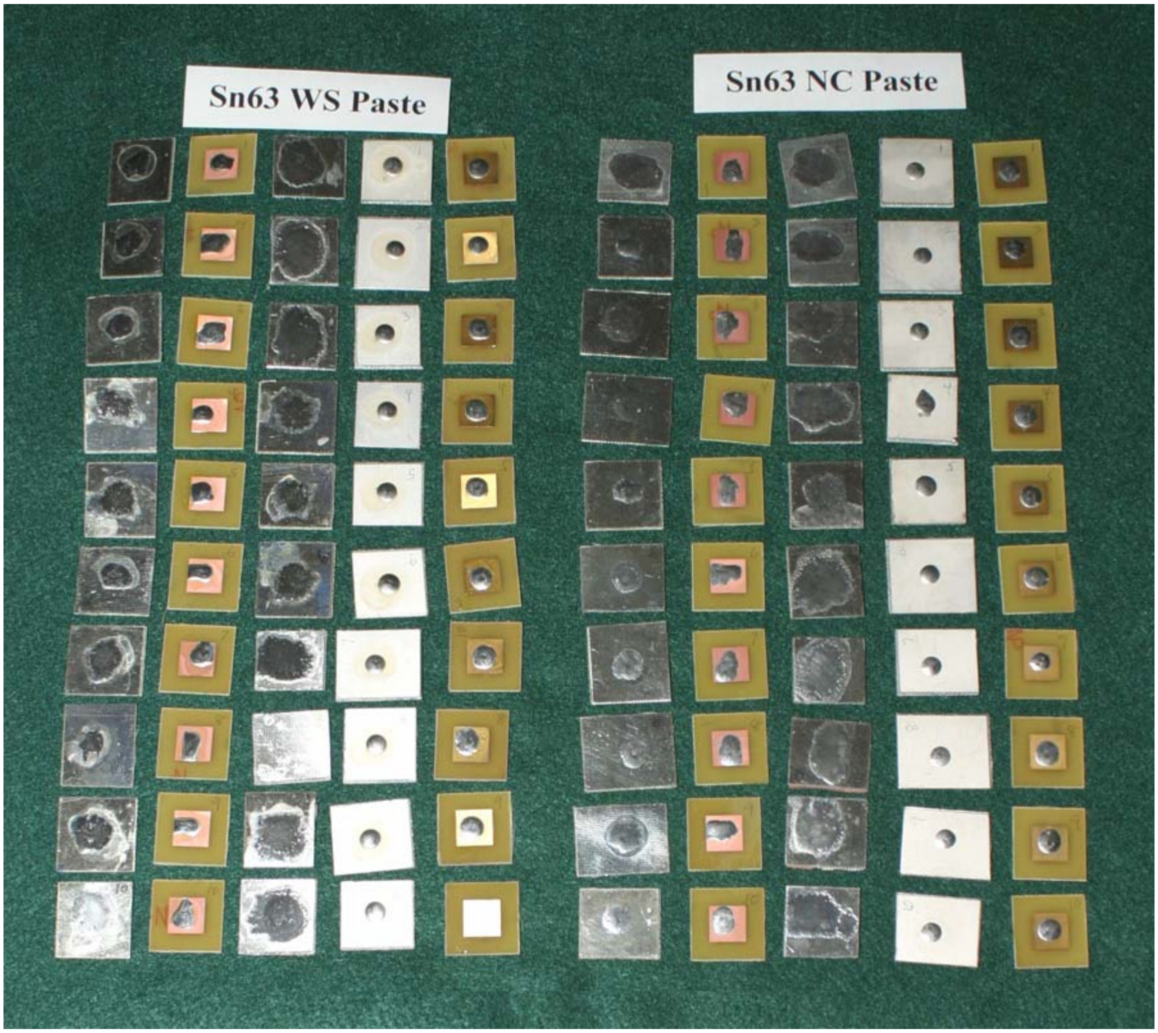

Figure 5

Figure 5 shows the wettability given by Sn63/Pb37 water soluble and no clean pastes on five different types of board finishes – the far left column of ten test coupons in each case contain the HAL finish followed by OSP, Immersion Tin, Immersion Silver and finally ENIG.

Test results show that Immersion Ag, in both cases, yielded poor wetting followed by ENIG and OSP. In the case of Immersion Sn (column 3), the solder paste has diffused into the underlying copper surface, forming intermetallic crystals.

Figure 6

Figure 6 shows the magnified versions of the diffusion of pastes through the thin layer of immersion tin (as it melts easily at re-flow temperatures) into the copper surface resulting in the formation of intermetallics, which could result in poor solderability. Going back to figure 5, the HAL coupons showed a larger wetting area than the ones produced by OSP, Immersion Ag and ENIG. The spread was even with no diffusion into underlying copper.

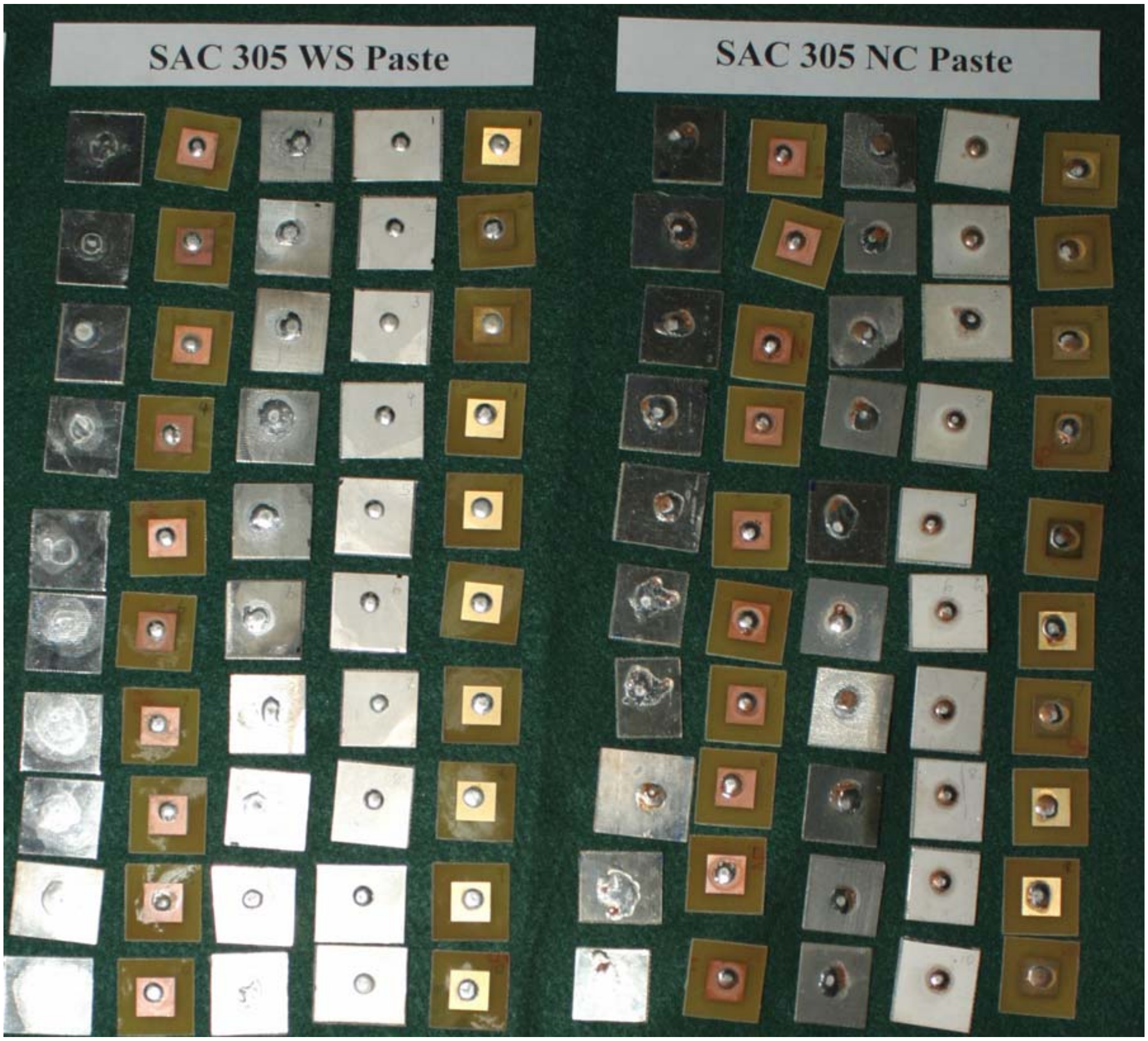

Figure 7

Figure 7 shows wetting characteristics of SAC305 water soluble and no clean pastes on similar sets of board finishes. Again, Immersion Ag yielded the poorest wetting followed by OSP, ENIG and finally, Immersion Sn. HAL coupons in both cases showed larger wetting areas.

Figure 8

Figure 8 shows wetting characteristics of the Sn/Cu/Co alloy. The results were very similar to those of SAC305 across the board with all different types of finishes. This indicates that the low cost Sn/Cu/Co performs at least as good as the high cost SAC305 in wetting boards.

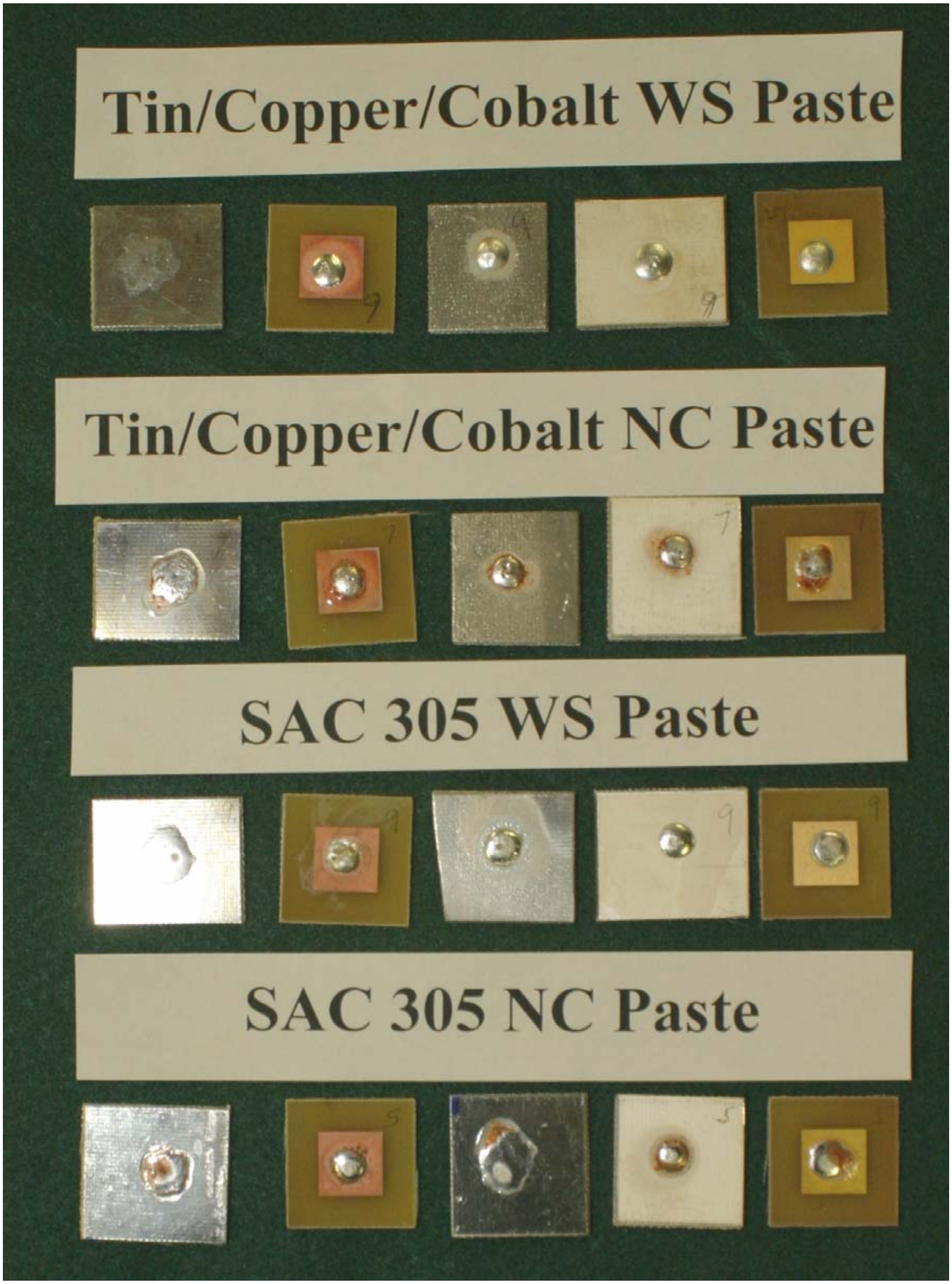

Figure 9

For ease of comparison, Figures 9 shows the wetting characteristics of Sn/Cu/Co and SAC305 on all five board finishes put together in one picture. Again, in summarizing, the HAL coating gives the best wetting followed by Immersion Sn, ENIG, OSP and Immersion Ag.

Wetting Tests - Summary

ENIG – Poor wetting . However, the standard Sn63/Pb37 paste gives about 20% more spread than the SAC305 and Sn/Cu/Co pastes.

Immersion Silver – Poor wetting with all pastes.

OSP – Poor wetting with Cobalt and SAC alloys. Standard Sn63/Pb37 shows about 30% better wetting.

Immersion Tin – Standard Sn63/Pb37 tends to totally defuse through the very thin coating of molten tin onto the underlying copper. It shows evidence of intermetallics at the outer edges of the spread.

HAL – Sn63/Pb37 shows better wetting with no intermetallics on the edges of the spread. It also shows moderate wetting with both Cobalt and SAC alloys.

Wetting Tests - Conclusions

1. The HAL board coating gives the best wetting overall independent of the paste.
2. Cobalt gives as good wetting as SAC. Therefore the low cost Cobalt is a better alternative to SAC.
3. Paste tends to diffuse through a tin layer into copper, causing copper nodules.
4. Immersion Silver exhibited poorest wetting across the board.
5. ENIG and OSP were a little better with Sn63/Pb37 pastes.

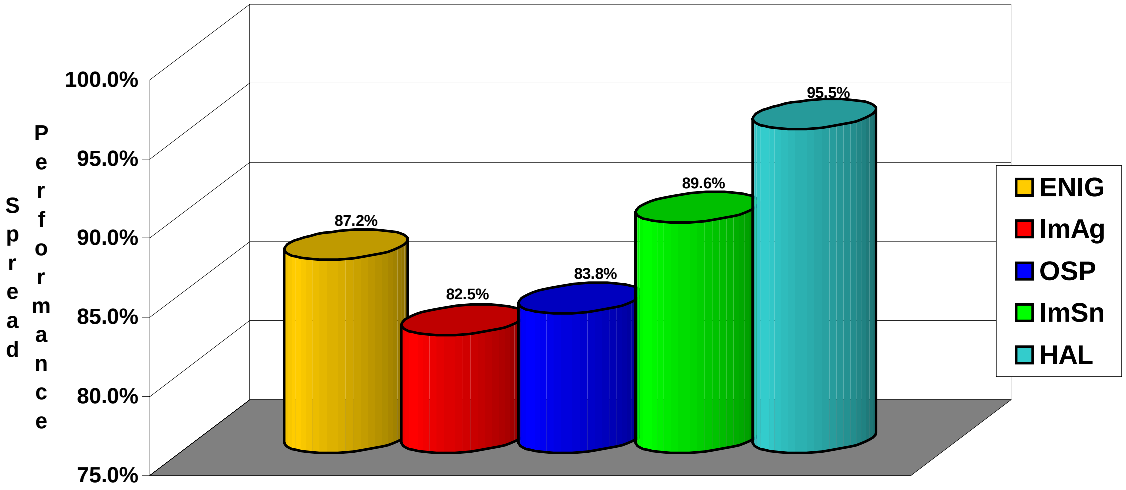

Figure 10: Surface Finish Comparison

Figure 10 shows the average comparative spread of all alloys tested for each board finish. The results show that, no matter what the lead-free paste alloy, all pastes work better on a hot air leveled board finish.

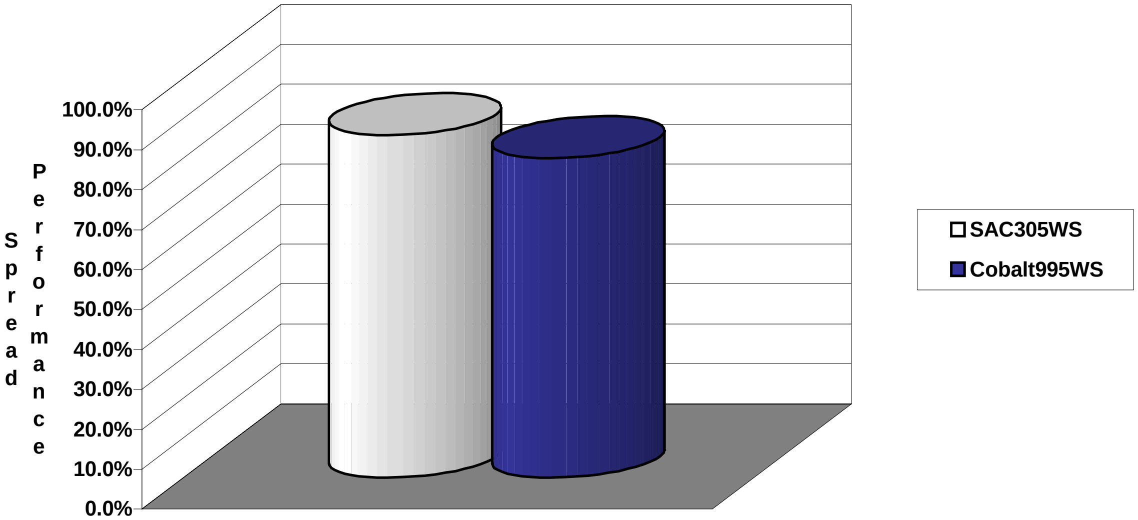

Figure 11: Lead-Free Water Soluble Comparison

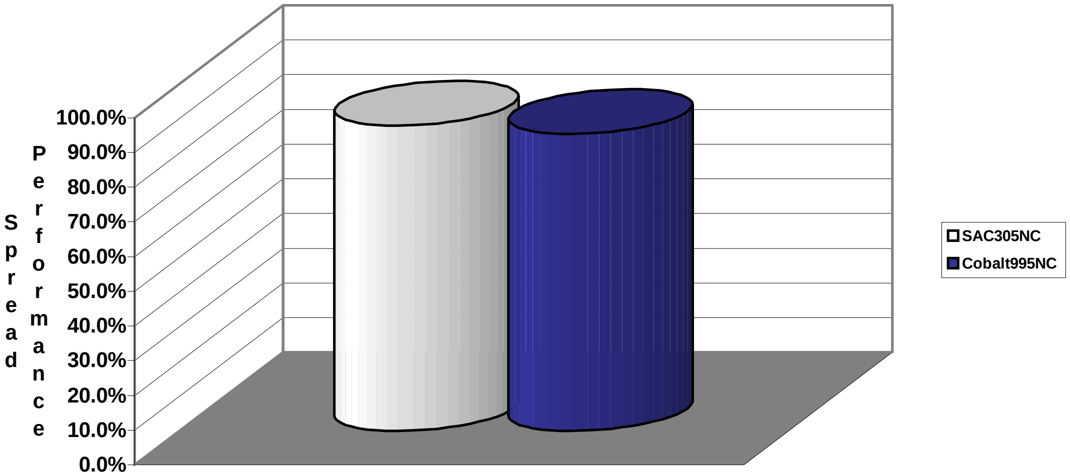

Figure 12: Lead-Free No-Clean Comparison

Figures 11 and 12 show that both Lead-Free alloys perform about the same, no matter which board finish is used.

Summary

As the electronics industry transitions to Lead-Free soldering, hot air leveling should continue to be the preferred method of preserving solderability on bare printed circuit boards. Its lower cost, while increasing slightly, should continue to maintain a cost/benefit advantage over alternative board finishing methods. Additional advantages include excellent solderability, wetting and spread, long shelf life, and durability.

Board fabricators will be able to provide Lead-Free HAL boards with thinner, shinier, and more coplanar surface mount pads than their tin/lead counterparts. Wetting times and action will be similar, if not better, than those presently achieved with eutectic tin/lead solder.

For circuit board assembly operations, board assemblers have several types of alloys to choose from, depending upon the criteria deemed important to each assembler. All testing shows that an Sn/Cu/Co alloy will provide lower cost, better wetting and wicking, brighter and shinier solder joints with less graininess, and greater ease in keeping a solder pot bath in specification.

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