Hot Air Leveling in the Lead-Free Environment

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As the electronics industry transitions to lead-free soldering, hot air leveling should continue to be the preferred method of preserving solderability.

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 China, California, and other regions. 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 manufacturing processes. These studies used PCBs 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.

Lead-Free Alloys

In the recent past, more than 80% of all produced PCBs worldwide were hot air leveled. Today, still more than 60% of all PCBs produced still 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) demonstrates the solderablility of the PCB, c) produces a product with excellent shelf life, and d) produces a product that is 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 HAL to be successful, it should reproduce many of these advantages. A major cost of the HAL process is the solder. There have been numerous lead-free alloys developed as a result of pending EU legislation. Many of these alloys can be eliminated from consideration for any of the following reasons: cost considerations, material availability of alloy constituents, compatibility with other solder alloys or soldering processes, and reliability considerations.

The remaining alloys can be placed into one of two major groups. 1) Tin/Silver/Copper alloys; and 2) Tin/Copper alloys.

Tin/Silver/Copper

These alloys contain a minimum of 95% Tin, 1-4% Silver, and 0.1-1% Copper.

They are referred to as SAC alloys (SnAgCu). Alloys will vary widely from one solder vendor to the next. Of all the alloys in this group, the SAC 305 alloy (Sn/3.0/Ag/0.5Cu) has shown the most promise. It melts at 217°C compared to 183°C for the eutectic tin/lead alloy. A reasonable amount of long term reliability and other data are also available for this alloy. The recommended operating temperature for SAC305 ranges from 255°C to 265°C.

Tin/Copper

These alloys contain in excess of 99% Tin with varying amounts of Copper. The generally accepted eutectic composition contains 99.3% Tin and 0.7% Copper with a melting point of 227°C. However, experience shows that tin/copper alloys by themselves when used in the HAL process produce boards with dull, grainy, large crystal coatings. In the past, such coatings were indicative of poor quality PCBs. Boards exhibiting dull coatings proved very difficult to solder in the final assembly stages. For this reason, small additions of grain refiners are added to the base tin/copper alloys to produce bright, shiny coatings. These grain refiners are elements such as cobalt, gallium, germanium, or nickel. An example of this alloy would be the cobalt containing 99.7Sn/0.3Cu/0.06Co alloy (Ref. 1) which melts at 227°C.

Even though there is a substantial difference of 44°C between the melting points of tin/copper based alloys and the 63/37 alloy, the actual difference in the process temperatures these two alloys are used at is only 10°C–20°C. Tin/lead alloys are usually run at temperatures of 250°C–260°C, whereas tin/copper/cobalt alloys are operated at temperatures in the range of 260°C–270°C in both vertical and horizontal hot air leveling machines. Table 1 details the physical properties for some lead-free and tin/lead alloys.

→ 52

	SAC 305	Sn/Cu/Co	63/37
Melting Point (°C)	217	227	183
Density (g/cm³)	7.4	7.3	8.4
Operating temp. (°C)	265	265	245

Table 1. Physical Properties.

Hot Air Leveling in the Lead-Free Environment

Cost of Lead-Free Alloys

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 SAC 305 alloy costs three times that of 63/37 alloy. So, one can readily see that the conversion to lead-free will be anything 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 board fabricators is the tin/copper based alloy for hot air leveling.

Wetting Balance Tests

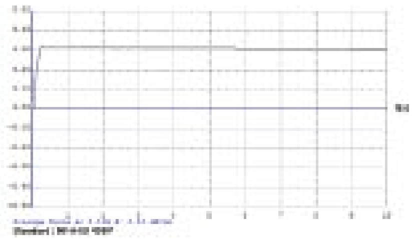
It would be expected that the ideal lead-free replacement solder, in order to yield results comparable to 63/37 tin/lead solder in a hot air leveling process, would wet copper surfaces as good as 63/37 tin/lead solder.

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 63/37 alloy. Testing was conducted on a Metronelec Wetting Balance.

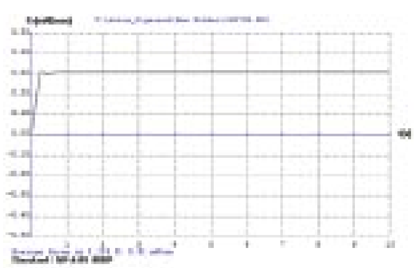
Wetting balance tests were first conducted at 250°C for 63/37 (its recommended operating temperature) to establish a baseline to which the lead-free alloy could be compared. Next, wetting balance tests were conducted on the Sn/Cu/Co alloy at temperatures of 250°C, 255°C, 265°C, and 275°C (Table 2).

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 63/37 is statistically different from the lead-free at all temperatures. A closer



Graph 1. Average of 20 tests for baseline group – 63/37 tested at 250°C.



Graph 2. Average of twenty tests for 99.7Sn/0.3Cu/0.06Co at 265°C.

examination of the initial 1-second of wetting is important given the potential 2 seconds of average contact time in a hot air leveling process. In an ideal wetting scenario, the initial rise to maximum wetting should be as steep as possible. The slope of the 63/37 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 closely approaches the ideal shape.

For the 63/37 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 99.7Sn/0.3Cu/0.06Cobalt 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.

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

Table 2. 63/37 Alloy

For the 99.7Sn/0.3Cu/0.06Cobalt at 275°C, the wetting was also instantaneous. The rate of rise is very similar to the 63/37 group, and the maximum wetting force is very slightly lower at 0.31mN/mm.

The wetting characteristics for the 99.7Sn/0.3Cu/0.06Cobalt can be made to simulate that of 63/37 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 63/37.

Temperature	250°C	255°C	265°C	275°C
Max. wetting force (mN/mm)	~0.30	~0.30	>0.31	>0.31
Time to 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

Table 3. Sn/Cu/Co Alloy.

Copper Loading Capacity of Solder

There is substantial data available as to how much copper content can be tolerated in a 63/37 tin/lead HAL operation. Experience gained through years of tin/lead HAL revealed that the performance of solder was adversely affected when the copper content reached approximately 0.5% at operating temperatures of between 250°C and 260°C.

Unfortunately, this same data does not yet exist for lead-free solder alloys. The eutectic tin/copper alloy of 99.3%Sn/0.7%Cu already has a copper content greater than what can be tolerated in a tin/lead HAL 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 → 54

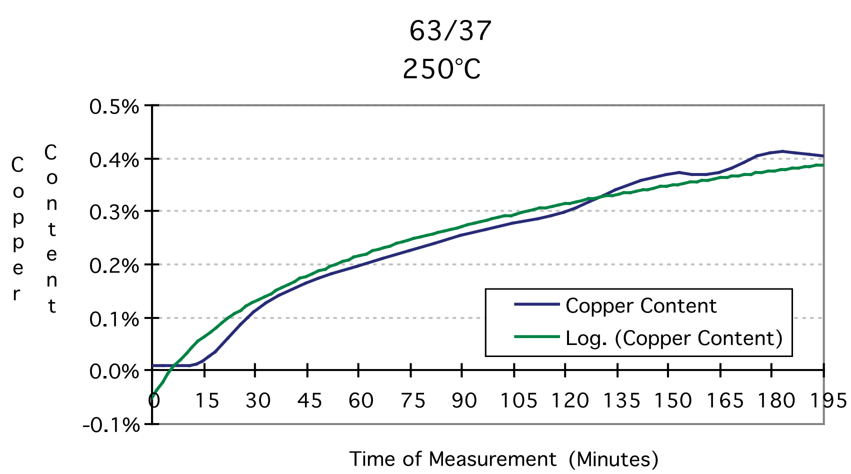
Hot Air Leveling in the Lead-Free Environment

Time (Minutes)	63/37 Alloy Temp. 225°C	63/37 Alloy Temp. 250°C	63/37 Alloy Temp. 260°C	63/37 Alloy Temp. 270°C	Sn/Cu/Co Alloy Temp. 255°C	Sn/Cu/Co Alloy Temp. 260°C	Sn/Cu/Co Alloy Temp. 265°C	Sn/Cu/Co Alloy Temp. 270°C	Sn/Cu/Co Alloy 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%	0.693%	0.782%	0.809%	0.893%	1.017%
180	0.206%	0.408%	0.445%	0.460%	0.702%	0.787%	0.824%	0.881%	-
195	0.211%	0.402%	0.444%	0.468%	0.707%	0.800%	0.838%	0.887%	-

Table 4. Results of solder samples analyzed on an emission spectrophotometer.

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 HAL operating temperatures. The solder pieces were immersed in circulating solder baths for 15 minute periods. The copper 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. Table 4 summarizes the data thus obtained.

The above data indicates the rate at which 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 63/37 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.



Graph 3. 63/37, 250C.

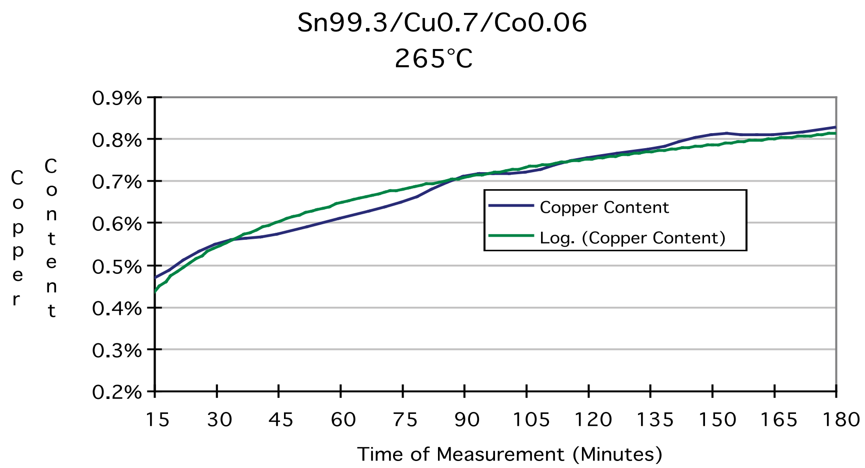
Discussion

A review of the 63/37 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 as it approaches this level of 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 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 slower rate for fresh Sn/Cu/Co with an initial copper concentration of approximately 0.3% than for fresh 63/37 with 0% copper across all temperatures studied. Further, both the lead-free alloy and 63/37 were → 56

Hot Air Leveling in the Lead-Free Environment



Graph 4. Sn99.3/Cu0.7/Co0.06, 265C.

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 resulted after three passes. See Table 5.

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 85% 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 surface?" 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. Table 6 shows results for one of these trials from a horizontal hot air leveling machine.

No. of HAL cycles	Copper thickness (Mils)		Reduction in thickness (Mils)	
	Sn/Cu/Co	Sn/Pb	Sn/Cu/Co	Sn/Pb
Start	0.8 mils	1.0 mils	0 mils	0 mils
1 cycle	0.8 mils	0.9 mils	0 mils	0.1 mils
2 cycles	0.7 mils	0.9 mils	0.1 mils	0.1 mils
3 cycles	0.6 mils	0.8 mils	0.2 mils	0.2 mils

Table 5. Copper (Cu) Thickness Reduction 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.

Table 6. HAL Coatings Thickness Data.

Summary

As the electronics industry transitions to lead-free soldering, hot air leveling should continue to be the preferred method of preserving solderability. Its cost, while increasing slightly as a result of the more expensive lead-free solders, should continue to maintain a cost/benefit advantage over alternative board finishing methods. Additional advantages, such as excellent solderability, long shelf live, and durability should not be diminished in a lead-free environment.

Board fabricators will be able to provide lead-free HAL boards with thinner, shinier, 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. ■

References

1. Patent pending, Metallic Resources, Inc., Twinsburg, OH 44087.

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