IPC PERM DoD Phase 3 Test Program: Copper Dissolution Testing Report for the Selected Pb-free Solder Alloys: SAC305, SAC4.8Bi, SAC6.0Bi and SAC7.5Bi

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ABSTRACT
The Restriction of Hazardous Substances (RoHS) Directive has limited the use of lead in the European Union since its implementation in 2005. This material restriction has driven companies such as Collins Aerospace and its suppliers to investigate the application of lead-free (Pb-free) solder alloys. Since Collins Aerospace products operate in harsh conditions in life-critical applications, it is imperative that the impact of transitioning to Pb-free solder alloys on reliability and manufacturing must be well understood. In conjunction with the IPC Pb-free Electronics Risk Management (PERM) Department of Defense (DoD) Phase 3 Pb-free Soldering consortium program, Collins Aerospace conducted copper dissolution testing for the IPC PERM DoD Phase 3 program to identify acceptable replacements for tin-lead (SnPb) solder. The rate at which any solder alloy dissolves copper is critical for establishing acceptable manufacturing processes to avoid damaging copper printed circuit board connections that are in contact with solder during reflow. This paper describes the approach for measuring the copper dissolution rates of five Pb-free solder alloys. The assessment discussing how the measured values compare to published copper dissolution rates for SnPb and SAC305 solder alloys is detailed and solder process graphs for selective/wave soldering processes are documented.

Key words: Pb-free solder, Copper dissolution

INTRODUCTION
Collins Aerospace has been a primary participant in the IPC PERM DoD Phase 3 industry consortium effort to understand Pb-free soldering materials and processes. This paper documents the Collins Aerospace copper dissolution testing effort for the IPC PERM DoD consortium program. The IPC PERM DoD Phase 3 consortium is a continuation of the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JG-PP) Pb-free Solder Project [1], an established industry consortium project focused on evaluating the reliability of Pb-free solder alloys for the requirements of the aerospace and military electronics products, and the NASA DoD Phase 2 Project [2].

Copper Dissolution Testing Background
Collins Aerospace participated in the IPC PERM DoD Phase 3 Project to understand the impact that Pb-free solder alloys have on copper dissolution rates for selective/wave solder processes. Pb-free solder alloys typically have higher melting temperatures than their SnPb counterparts and thus need different assembly processing profiles. With these Pb-free solder alloys, the interaction of the molten solder and the copper circuit board structures (i.e., traces, vias, pads, etc.) is much faster than that of SnPb solders, which accelerates the degradation of the plated copper structures. The NASA DoD Phase 2 Project included copper dissolution testing of SAC305 and SN100C Pb-free solder alloy results that were reported at the 2013 International Conference on Soldering and Reliability [3]. The IPC PERM DoD Phase 3 testing assessed the dissolution rates of four Pb-free solder alloys: SAC305, SAC4.8Bi, SAC6.0Bi, and SAC7.5Bi with SnPb used as a baseline. Copper dissolution behavior is of particular concern if components are to be reworked, which is much more commonly done on high-reliability electronics than on consumer electronics. Reworking product that has Pb-free solder joints may impact repair operations as copper dissolution can remove over half of the Plated Through Hole (PTH) copper in a single rework cycle. Multiple rework cycles may therefore not be acceptable for Pb-free soldered products, due to the impact of copper dissolution.

<u>Kinetics of Copper Dissolution</u>
Copper dissolution is a well-documented topic [7-12] that is considered a result of these two mechanisms:

1. Departure of atoms from the solid surface
2. Diffusion into the molten solder

Diffusion controlled processes result in a uniform attack while interface-controlled reactions may be recognized by preferential attack of grain boundaries. In this study, smooth copper/intermetallic interfaces without any indications of grain boundary attack were observed. In general, the dissolution will follow an exponentially decaying function:

$$C = C_s(1\text{-}e\text{-}^{kt})$$

Where C is the solute concentration at time t, C_s is the saturation concentration, k is the solution rate constant, (k=K*S/V), where K is the solution rate constant, S is the surface area, and V is the volume of liquid. This equation can be applicable to diffusion controlled and interface-controlled processes.

In this study, test vehicles were wave soldered, in which the volume of solder was orders of magnitude larger than the amount of copper in a given PTH. Thus, calculation of the dissolution rates by measuring in the concentration of copper in the solder alloy bath were too small eliminating the use of that methodology. Instead, the dissolution rate was estimated by measuring changes in PTH copper wall thickness over time with the decrease in copper thickness over time corresponding to its dissolution rate. Thus, the thickness of copper plating in the PTH, L, was assumed to follow the equation: $L = L_0 - k*t$, where L_0 is the copper thickness at time = 0, t is the cumulative time that the copper was exposed to a given solder alloy, and k is the dissolution rate for copper in that particular solder alloy.

Copper Dissolution Impact on Assembly Practices

The impact of copper dissolution on printed circuit board assembly practices can be significant if it is not characterized and controlled. The allowable process window for the removal and repair of PTH components in a Pb-free soldering process is significantly smaller than the process window used for SnPb soldering processes. Copper dissolution defects are particularly hazardous because they are not readily detectible by visual inspection or most functional test protocols since circuits may still have electrical continuity, even if dissolution defects substantially decrease their current-carrying capacity. Two important impacts of copper dissolution are described below:

PTH component rework/repair procedure

Traditional SnPb solder alloys provide a large rework/repair process window with little concern for copper dissolution. Potential printed circuit board (PCB) laminate defects, such as delamination or component damage due to extended heat exposure, are much more concerning. The repair/rework process window for Pb-free solder is typically smaller and can be concerning for heavy copper/thermally loaded printed circuit board assemblies since it limits the allowable exposure time and additional thermal excursions. Alternative component removal methodologies, such as a hot air pen or rework attachment using a selective solder process, should be considered as possible methods for removing components that reduce the effects of copper dissolution for Pb-free soldering processes.

The use of alternative printed circuit board surface finishes

Some printed circuit board assembly properties, such as the number of copper layers, the minimum plating thickness of the copper structures, and the laminate construction, may make Pb-free solder alloy rework/repair unachievable. Other PCB surface finishes, such as electroless nickel/immersion gold (ENIG) can reduce dissolution, as shown in Figure 1.

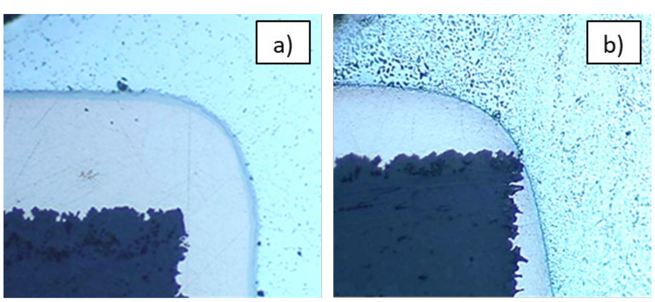

Figure 1: Impact of PCB surface finish on copper dissolution; a) ENIG, b) immersion tin

Test Vehicle

The test vehicle used for the copper dissolution testing consisted of a break-off coupon with six PTH dual in-line package (DIP) patterns. The six specific PTH diameters were 0.015”, 0.019”, 0.024”, 0.028”, 0.036”, and 0.040” finished diameter. The test coupon was 4.7” x 1.6” x 0.092” thick. Test coupons were fabricated with two different laminates: an IPC-4101/126 (Isola 370HR) laminate and Isola 408. Both used an immersion silver surface finish. Figure 2 illustrates how half of the PTHs were exposed to molten solder and the other half of the PTHs were covered with Kapton™ tape to prevent contact between the copper in those PTHs and the solder.

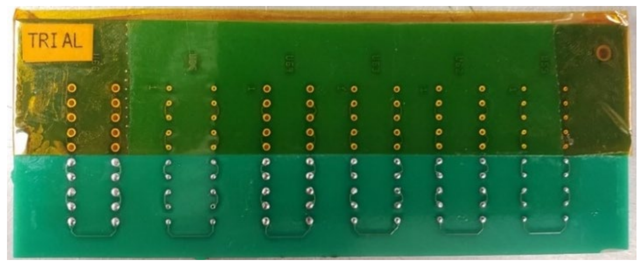

Figure 2: Copper dissolution test coupon

Solder Alloy Candidates

Four Pb-free solder alloys were used in the copper dissolution testing: SAC305, SAC4.8Bi, SAC6.0Bi and SAC7.5Bi. Since copper dissolution rates for the three SACBi solder alloys had not been established by the solder alloy supplier, these test results would be the first documentation of their dissolution characteristics. A SnPb solder alloy (Sn63/Pb37) was also included for baseline comparison to the Pb-free results. Table 1 shows the temperatures at which each solder alloy was evaluated. These test temperatures were selected based on a review of industry published investigations, previous internal testing [3] and existing industry “typical” soldering process temperature ranges.

Table 1: Solder alloy wave pot temperatures

Solder Alloy	Wave Pot Temperature (°C)
SnPb	260
SAC305	260
SAC4.8Bi	240
SAC6.0Bi	240
SAC7.5Bi	240

Experimental Setup

Figure 3 shows the AirVac PCBRM-12 solder fountain mini-wave system used for this test. An FWL-1218 nozzle was used with all tested solder alloys. An aluminum fixture supported the test vehicle for the soldering exposures. The fixture provided a stable platform for repeating the exposure cycles and minimizing setup variability. Prior to processing a solder alloy copper dissolution coupon, several trial coupons were used to validate the process temperature, solder flow rates, solder pump speed, preheat time and nozzle flow consistency. All test coupons were processed starting at room temperature to avoid any unaccounted temperature impacts on the dissolution rate. Thirty test vehicles per solder alloy were processed in the mini-wave system for various exposure times. Before processing test coupons for a specific solder alloy, the solder pot was emptied and flushed with pure tin to avoid solder alloy cross contamination. The SnPb solder alloy test coupons were processed last.

The dissolution exposure times/step intervals were selected based on the goal of capturing a large data set ranging from minor dissolution to nearly complete dissolution of the PTH copper layers. Two different strategies were used for exposing the copper to molten solder: continuous exposure and interval exposure. In continuous exposure, three coupons each were processed, without being taken out of the solder fountain, for 30, 60, 80, or 120 continuous seconds. For interval exposure, three other coupons were initially processed for 45 seconds and then exposed again in 15-second intervals to accumulate total times of 60, 75, 90, 105, or 120 seconds. In the interval exposure testing, the solder was allowed to cool and solidify between each step before being processed again, if necessary.

Figure 3: AirVac Mini-wave system with test coupon/soldering fixture

Copper Dissolution Measurements

All test boards subjected to metallographic cross-sectioning preparation for examination under a microscope to measure the PTH copper plating thickness in the as-fabricated condition and the soldered exposure condition. By measuring the PTH copper plating thicknesses, the dissolution rate could be determined for each alloy as the slope of the line when change in thickness was plotted as a function of time.

The test coupon copper thicknesses were measured using metallographic cross-sectioning per the following details:

- Measurements were taken at 3 locations (top, middle, bottom) on each side of the PTH (Figure 4).
- The "Original Thickness" measurements were taken from the PTHs that were covered with Kapton™ tape and therefore not exposed to the solder.
- The "Final Thickness" measurements were made on the PTHs after the soldering process exposure.
- The test vehicle was oriented so that the bottom refers to the solder source side.
- Measurements were only taken on every other PTH such that PTHs 2, 4, 7, and 9 were not measured (see Figure 5).
- A total of approximately 32,400 thickness measurements were recorded in this investigation.

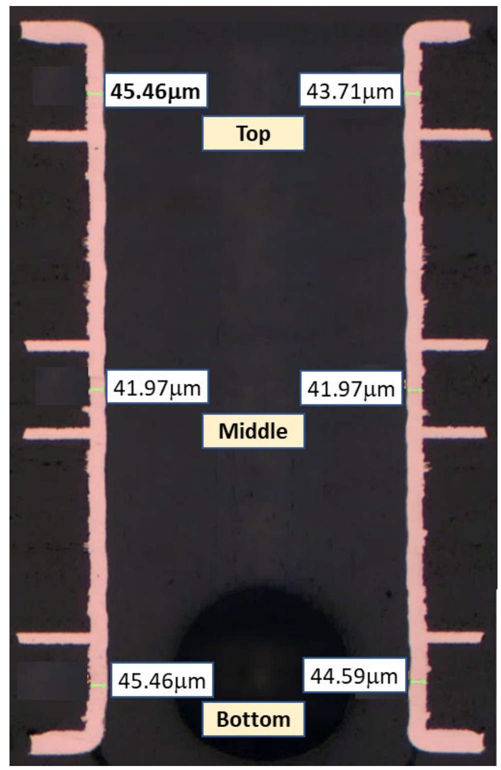

Figure 4: Dissolution measurement locations

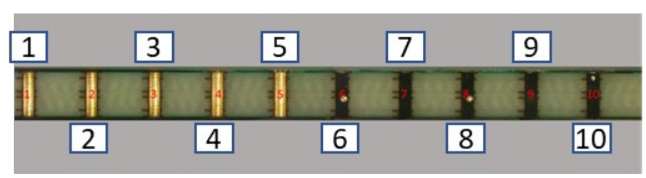

Figure 5: PTH cross-sectional measurement references

Results

The differences in copper dissolution between the top and bottom PTH knee locations became more evident as the exposure time increased. Most of the analysis focused on the bottom measurements as they represented the most consistent, repeatable change for the exposure durations used. Figure 6 illustrates representative solder alloy metallographic cross-sections for the different solder alloys.

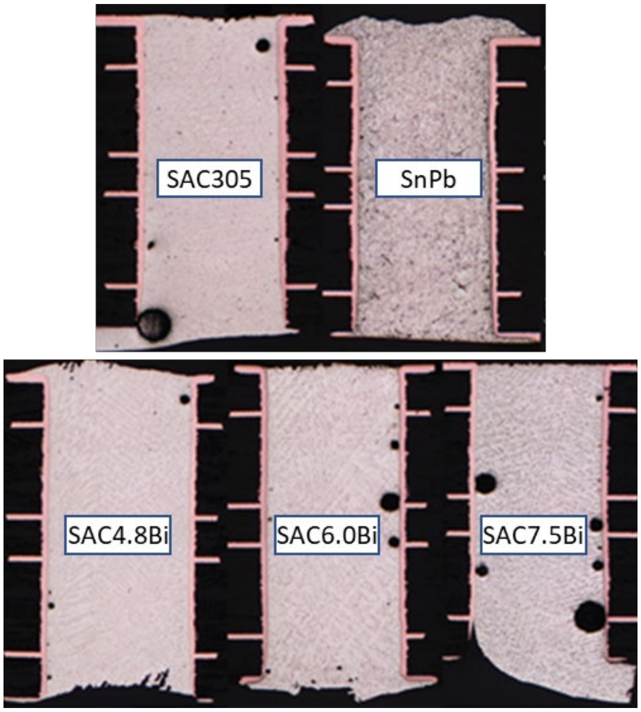

Figure 6: Example metallurgical cross-sections, 0.036" PTH, 120 Second Exposure

The left half of the cross section of the PTH exposed to SAC7.5Bi show in Figure 6 was completely dissolved for this exposure time. One of the data analysis variables was how to deal with cases in which copper was completely dissolved. This topic is discussed later in the paper.

Figure 7 shows an example of how the solder exposure approach affected copper dissolution. These plots show the amount of copper that was removed for different exposure times and include the raw data, as symbols, as well as best-fit lines, the slopes of which correspond to the estimated dissolution rates. The plots are for SnPb solder, but the other solders generally showed similar trends, which include:

- Interval exposure led to higher overall copper dissolution (steeper slopes) than continuous exposure. This is likely a result of the local concentration of dissolved copper in the solder increasing over time, which would slow further dissolution. Since interval exposure better mimics the conditions associated with rework processes, and the results for interval exposure are more conservative, the data analysis focused on the interval exposure data.
- In most, if not all configurations, the highest dissolution occurred in the 36 mil diameter PTHs. It is reasonable to expect that larger diameter PTHs will allow for more flow into and out of a via, thereby reducing the concentration of dissolved copper. It is not clear why the 40 mil PTHs experienced less copper dissolution than the slightly smaller 36 mil PTHs. Again, for conservatism, the data from the 36 mil holes were primarily used in subsequent analyses since they represented the highest dissolution levels.
- These plots show the results for measurements made at the 'bottom' of the PTHs. The justification for using those data is discussed later in this document.

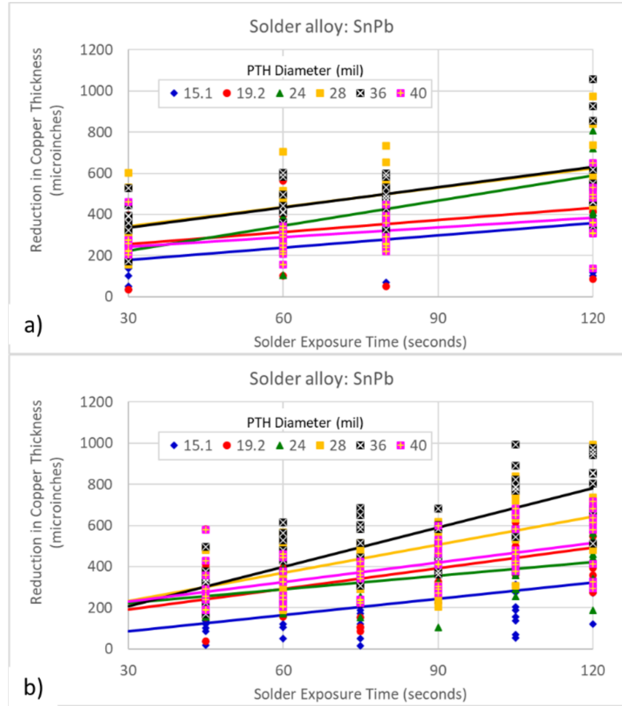

Figure 7: Effect of solder exposure method on copper dissolution with SnPb solder alloy for different PTH diameters; a) continuous exposure, b) interval exposure

Figure 8 plots data for measurements with SAC305 solder, in different formats. The top plot shows all measurements while the center plot shows averaged values for each solder exposure time. These approaches give nearly identical slopes, as shown in the right plot. Differences are a result of the different exposure times not having the same number of measurements.

The results shown in Figure 8c) were calculated using conventional least-squares curve fit analysis to determine the slope of each line and a t-test based method to determine an uncertainty range for a 95% confidence level [12]. That plot shows that the two approaches generated very similar results, the 36 mil PTH had the highest dissolution rate, and the error bands were similar (in this case) regardless of analysis approach.

For clarity, future plots show data in the format shown in Figure 8b), with only the averaged value for each time and PTH diameter combination. However, the slopes and confidence levels that are reported are based on the full data set, as shown in Figure 8a).

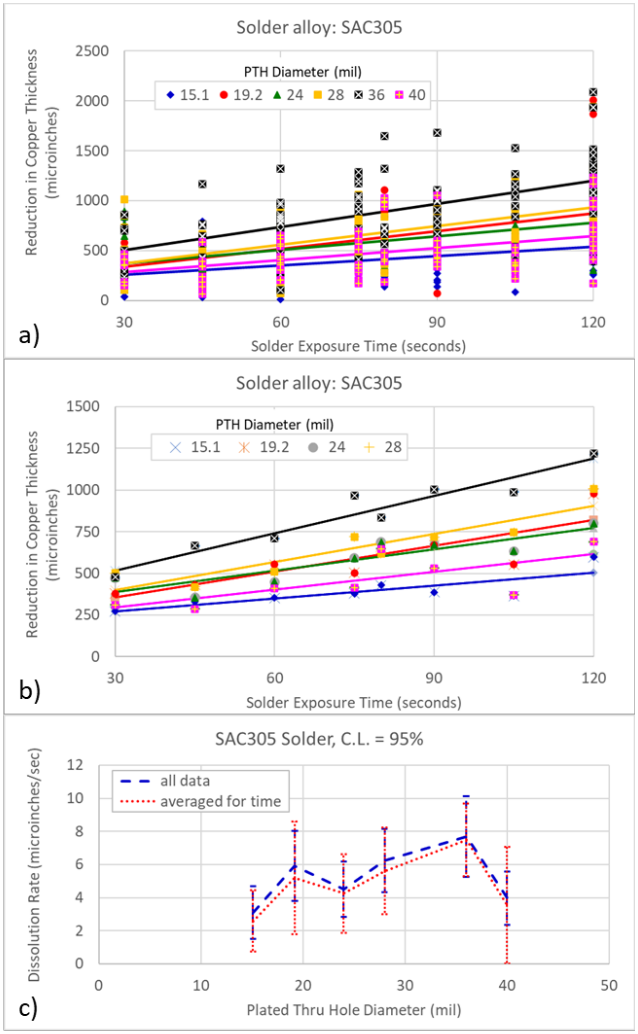

Figure 8: Effects of regression analysis approaches: a) using each measurement, b) using averaged values for each exposure time, c) best-fit slopes (dissolution rates) with 95% confidence bands for two approaches

The data shown in the previous slides were for measurements made at the 'bottom' of the PTHs, i.e., closest to the surface exposed to molten solder. Figure 9 illustrates why that location was used for estimating the dissolution rate. The figure shows measurements for the SAC4.8Bi solder alloy with the three plots showing data for the three locations on the plated through hole. It is clear that substantially more copper dissolved in the locations nearest the solder alloy. Since the objective of this study was to document the worst-case dissolution that copper would see, the measurements at the Bottom location were the most relevant. All data in the rest of this report results from measurements made at the Bottom locations of the PTHs.

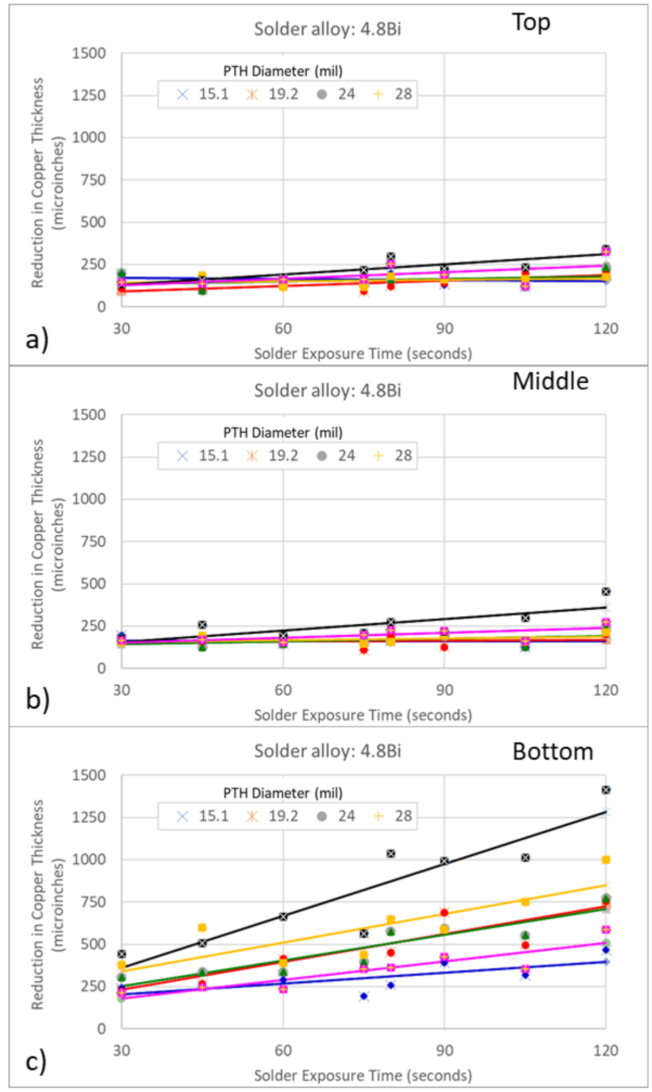

Figure 9: Copper dissolution on PTHs, a) top of PTH, b) middle of PTH, c) bottom of PTH

As shown in Figure 6, there were cases in which the entire PTH copper wall dissolved. The approach used for data analysis in those cases could potentially impact the results. Since the measurement approach was indirect (the measured thickness was subtracted from the expected starting thickness), a measured thickness of zero will underestimate the amount of copper that would have been removed in that time if the material had been initially thicker.

Figures 10 and 11 illustrate the effects that these completely dissolved measurements can have on the calculations and confidence levels. Figure 10a) shows all the data for the SAC7.5Bi solder alloy. Note that with the 36 mil diameter PTH, there is some 'droop' as the measurements for the three longest exposure times fall below the trend line of the initial measurements. Figure 10b) shows the same data but truncated such that measurements in which at least 2 values for a given time found that the copper was completely dissolved, measurements for that time value were not included. This shows a much higher slope, i.e., dissolution rate.

Figure 11a) shows the estimated dissolution rates, calculated from regression analysis, using the entire data set (including those PTHs that had complete dissolution). This figure includes error bars that indicate the 95% confidence level. Figure 11b) likewise shows the dissolution rates, but for the truncated data sets. It is clear that, for the 36 mil case, truncating the data (ignoring all data for a given time if at least two measurements showed complete dissolution of copper) increased the estimated dissolution rate from ~7 min/s on Figure 11a) to ~13min/s for Figure 11b). Truncating the data greatly reduced the number of values available for determining the confidence band, leading to the substantially larger range for the 95% confidence levels for the 36 mil PTH diameter dissolution rate. This is especially true for the 'averaged' data in which only the average value was used for each exposure time rather than each measured value. For this reason, reported confidence bands were calculated using all the data.

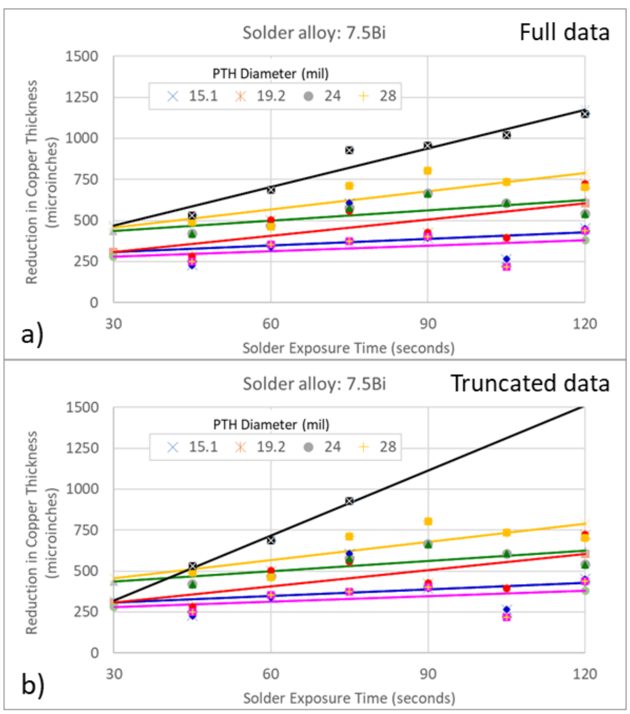

Figure 10: Dissolution data for different PTH diameters (SAC7.8Bi solder alloy); a) averaged dissolution for all raw data, b) averaged dissolution for truncated data

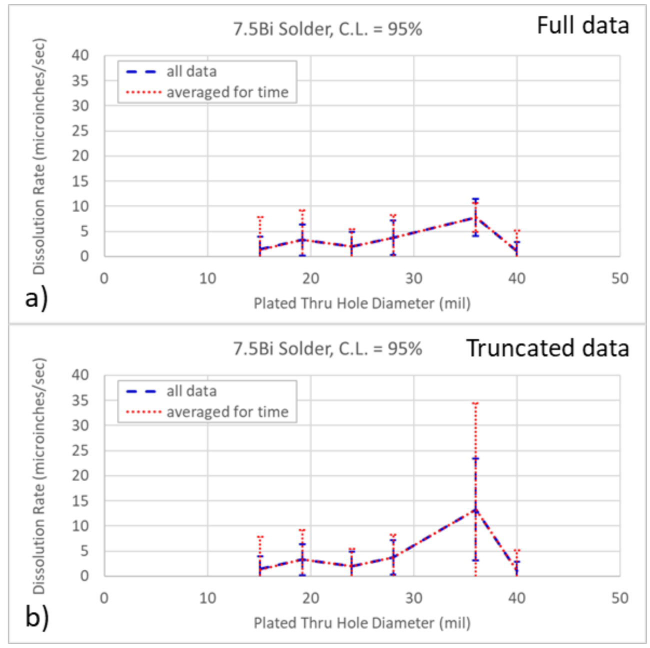

Figure 11: Dissolution rates with 95% confidence bands for different PTH diameters (SAC7.8Bi solder alloy) calculated from regression analysis; a) averaged dissolution for all raw data, b) averaged dissolution for truncated data

For reference, Figure 12 shows the copper dissolution plots for each of the alloys tested in this study. Averaged values included those measurements in which the copper was entirely removed. Hence there is 'droop' (the trend for increasing time curves flat rather than following a straight line) in the 36 mil PTH diameter data for alloys that had the high level of dissolution (primarily SAC7.5Bi).

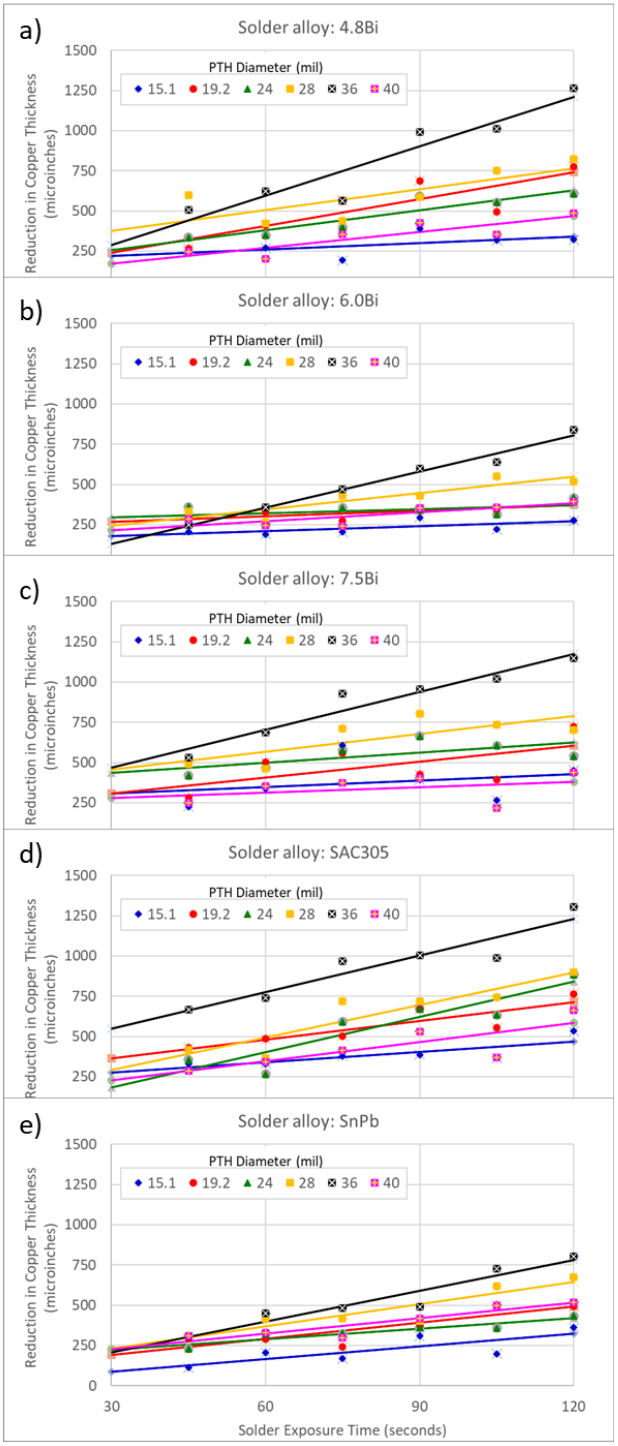

Figure 12: Copper dissolution; intermittent testing, PTH bottom, averaged for each measurement time: a) SAC4.8Bi, b) SAC6.0Bi, c) SAC7.5Bi, d) SAC305, e) SnPb

Figure 13 compares the calculated dissolution rates (slopes of the linear fit) for the different solder alloys for each PTH diameter size. In each case, the highest dissolution rate occurred in the 36 mil diameter holes. The plot includes error bars that show the range of values that define the 95% confidence band for each combination.

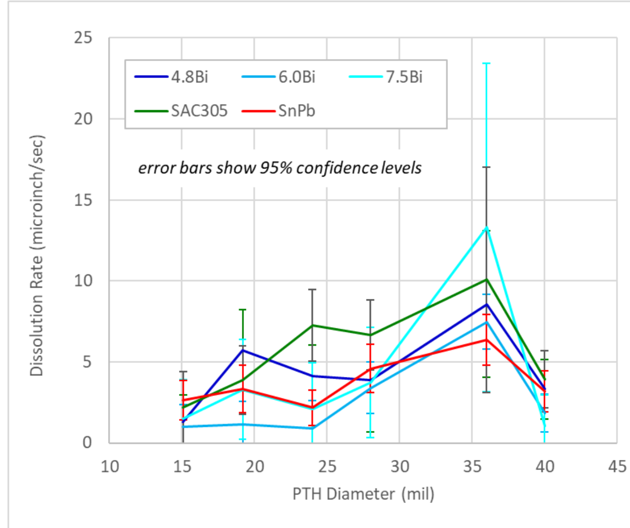

Figure 13: Best Fit Copper Dissolution Rates for Different Solder Alloys in Different Sized Plated Through Holes

Table 2 lists the calculated dissolution rates for all the combinations shown in Figures 12 and 13. Table 3 shows the confidence levels for each combination, normalized by the nominal value. For example, for the 36 mil diameter PTH, SAC305 had a measured dissolution rate of 10.1 microinch/sec with a 95% confidence band of 69% of nominal (0.69*10.1 = 6.97). Thus, based on these data we can be 95% confident that the actual dissolution rate is between 3.13 and 17.1 min/sec, i.e., between 10.1-6.97 and 10.1+6.97.

Table 2: Calculated dissolution rates for each alloy and PTH diameter (in microinch/second)

Solder Alloy	PTH Diameter (mil)					
	15.1	**19.2**	**24**	**28**	**36**	**40**
4.8Bi	1.3	5.7	4.1	3.9	8.6	3.3
6.0Bi	1.0	1.1	0.9	3.4	7.5	1.8
7.5Bi	1.5	3.3	2.1	3.7	13.3	1.0
SAC305	2.2	3.9	7.3	6.7	10.1	3.9
SnPb	2.6	3.3	2.2	4.6	6.4	3.2

Table 3: Normalized confidence bands for dissolution rates

Solder Alloy	PTH Diameter (mil)					
	15.1	**19.2**	**24**	**28**	**36**	**40**
4.8Bi	124%	44%	47%	83%	53%	55%
6.0Bi	134%	126%	188%	47%	22%	63%
7.5Bi	156%	93%	138%	91%	76%	183%
SAC305	101%	54%	30%	32%	69%	45%
SnPb	46%	44%	50%	33%	25%	40%

Discussion

Dissolution of the PTH knee is not readily detectible using typical assembly product stress screening, so strict assembly process control limits are necessary to ensure acceptable product reliability. By using the highest dissolution values, which were measured with the 0.036" PTH vias, and applying the 95% confidence interval to determine the worst-case dissolution rate, the minimum time needed to dissolve a given thickness of copper can be determined. Figure 14 shows the thickness of copper, which started at 2 mil thick, as a function of time when exposed to the different solder alloys using these worst-case dissolution rates. These values are used to define acceptable processing windows for IPC Class 3 (which must maintain at least a 1 mil minimum thickness) and IPC Class 2 (which must maintain at least a 0.5 mil minimum thickness) for electronic products. Process windows must ensure that the accumulated time at temperature do not exceed these thresholds. As detailed in this report, the measurements associated with copper dissolution testing are influenced by several factors resulting in measurement variation in a single testing program and between different testing programs. The process limits shown in Figure 14 are process window estimates and using reduced time exposures can be utilized until these values are validated with production assemblies.

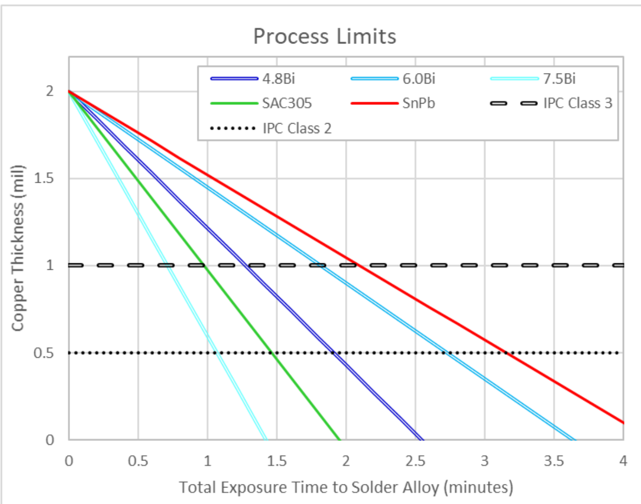

Figure 14: Estimated cumulative allowable process windows for 2 mil plating

Table 4 summarizes the maximum exposure times needed meet the IPC Class 3 and Class 2 conditions shown in Figure 14. Again, these indicate, at a 95% confidence level, the time before 2 mil copper could fail to meet the two IPC minimum allowable thicknesses. This shows that, for example, 2 mil thick copper should not be exposed to SAC305 solder for any longer than 1 minute if it needs to meet IPC Class 3 requirements and 1.5 minutes if it only needs to meet IPC Class 2. The values shown in this plot indicate total accumulated time; if a component is reworked multiple times, then the total time at temperature needs to be accounted for. SnPb solder has a dissolution rate that is slightly less than half that of SAC305, resulting in allowable cumulative solder exposures that are twice those of SAC305.

Table 4: Interval processing windows for 2 mil Copper plating for 0.036" PTH

Solder Alloy	Max. Cu Dissolution Rate (μin/s)	Allowable Cumulative Exposure Time (minutes)	
		IPC Class 3	IPC Class 2
7.5Bi	23.4	0.7	1.1
SAC305	17.0	1.0	1.5
4.8Bi	13.1	1.3	1.9
6.0Bi	9.2	1.8	2.7
SnPb	7.9	2.1	3.2

All measured copper dissolution values in the testing would be viewed as extreme durations for subjecting a PCB assembly to molten solder exposure. Other materials on the PCB, such as the board laminate and some component technologies, would be at higher risk of sustaining damage for such a long molten solder exposure duration. Additionally, a practical assessment of the Table 4 exposure time values highlights the values as optimistic due to many confounding factors. Those factors include:

Solder Flow Rate

Several industry investigations have produced significantly different copper dissolution values for both SnPb and Pb-free solder alloys. Vianco [5] and Hamilton [7] described how static versus dynamic solder flow rates produce different copper dissolution values. The nozzle geometry and flow rate for a given temperature on a flowing solder pot was shown to impact the measure copper dissolution rates. Shoji et al. [10] measured double the copper dissolution rates in dynamic conditions, established using rotating copper cylinders, as compared to a static condition for a fixed alloy composition/temperature.

Test Temperature

The dissolution rate, dD/dt, increases with temperature and is typically modeled as an exponential function of the absolute temperature, i.e., an Arrhenius relationship:

$$dD/dt = A^{-E/kT}$$

The term E/k is the activation energy divided by Boltzman's constant. Due to this temperature dependence, in order to directly compare copper dissolution rates from different investigations, the testing must be done using the same temperature. Inconsistencies in test conditions arise from the fact that test temperatures are generally based on specific soldering processes being used by the investigators. Typical industry wave solder processes can range from 250ºC to 350ºC (523K – 623K) depending on the solder alloy being used. This range of temperature can make it impossible to directly compare dissolution data from different tests. Therefore, investigation results are primarily useful for creating wave/selective solder process control protocols.

Dissolution Test Vehicle

The selected test vehicle often depends on the investigation objective. Showalter et al. [11] and Hillman et al. [4] used wire specimens, Hunt [6] use printed circuit board surface pads, Kennedy et al [3] and Byle et al [9] used both surface pads and wire specimens. Influences of specific test vehicles will introduce specific dissolution test conditions that are not necessarily replicated between different investigations. As demonstrated in the current study, a difference in the PTH diameter led to somewhat different dissolution rate measurements.

Solder Alloy Composition

The solder alloy composition plays a major role in the copper dissolution rate (Hunt [6], Hamilton et al [8], Byle et al [9], Kennedy et al [3]). Higher solder alloy tin composition tends to drive higher copper dissolution rates. The addition of various constituent elements such as nickel, bismuth, silver, and antimony all impact the copper dissolution rates.

Comparing copper dissolution rates from multiple published investigations can be challenging. Variations in test approaches and the inherent variability in measurements, as witnessed by the large confidence bands generated in this study, usually make these direct comparisons difficult. Interestingly, one study that was done by measuring the reduction in metal thickness in wires instead of vias found a nearly identical dissolution rate as in this study. McKenna et al. [4] conducted dissolution testing at a range of temperatures; interpolating their values for SAC305 with copper at 260°C shows a dissolution rate of ~0.3mm/s, which equals 11.8 min/s. That compares well to the 10.1 min/s measured in this study.

It is generally more beneficial to simply compare trends and map those trends to the specific soldering process to establish reasonable maximum temperature and exposure duration process limits. Since the current study and the Kennedy et al [3] study were conducted using the same equipment, dissolution test vehicle and test temperature for the SAC305 solder alloy, a reasonable comparative trend assessment is possible.

SAC305 Alloy Results Comparison Example

The Kennedy test and the current test both used a 260ºC test temperature and have data for a 0.036" PTH diameter. The Kennedy test reported a copper dissolution rate of 45 min/second for measurements made on surface mount pads. However, the measurements made in vias were substantially different. In that study, copper thickness measurements were only made at the middle of the PTH, not at the bottom. The dissolution rate calculated for those data found that the dissolution was ~6.6 min/s. Since the copper dissolution in the middle of the PTHs was quite small, those data were not analyzed as part of the normal data analysis in this study. However, the data were available for analysis – with the recognition that the small amount of dissolution would lead to substantial uncertainty in the results. The dissolution rate for the same conditions (SAC305, 36 mil diameter PTH and middle location of the PTH) was found to be 2.1±1.4 min/s with a 95% confidence level. This value is approximately one-third that found in the Kennedy test.

Conclusions/Summary

Conclusions drawn from the investigation include:

- The highest copper dissolution occurred at the solder source assembly side where the solder directly contacts the PTH. Risk of failure and/or signal integrity due to copper dissolution may be reduced by placing critical signal layers further from the area that directly interacts with the solder.

- The solder alloy type has a pronounced impact on dissolution rates. The difference in allowable exposure times makes solder alloy selection dependent on the expected number of rework cycle requirements for the product lifetime. Thus, the selection of the solder alloy is significant for establishing soldering and/or rework process control maximum exposure limits.

- PTH diameter is also a factor in observed dissolution. It is unclear why the maximum dissolution was observed on the 36 mil diameter PTHs rather than on the largest diameter vias in the study. From a fundamental physics perspective, it seems likely that there exists a worst-case via diameter in which dissolution is highest. As the diameter gets extremely small, the amount of solder in the PTH would get smaller and that small volume of solder would quickly become saturated with copper after some dissolution – thereby limiting the dissolution. In contrast, at large enough diameters, the volume of solder would be large enough that the internal flow, due to natural convection, etc. within the PTH, would be limited. This would again lead to the solder nearest the copper being relatively stagnant. At some 'optimum' diameter for dissolution, the via would be large enough to allow the solder alloy to easily move, but small enough that local physics, such as temperature gradient-driven buoyancy, to generate some flow. There is insufficient data available in this study to determine whether the fact that the 36 mil diameter PTH had the highest dissolution rates is a result of this 'optimal' geometry effect.
- The knowledge of how soldering process nozzle configuration and copper dissolution permits better soldering process/rework procedures that avoid copper dissolution issues.

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