

Impact of SMT Assembly Process on Tin Whisker Risk Mitigation

Chieh-Ju Lee, Guhan Subbarayan, Li Li and Jie Xue
Cisco Systems, Inc.
170 West Tasman Drive
San Jose, CA 95134
chielee@cisco.com

Peter Verbiest and Quyen Chu
Jabil Circuit, Inc.
30 Great Oaks Boulevard
San Jose, CA 95119

Abstract

Electroplated pure tin or high-tin finishes on Pb-free components remain a reliability concern due to spontaneous tin whisker growth which may cause failures in electronic equipment. To ensure system reliability, component suppliers and system manufactures have placed significant emphasis on component level tin whisker testing using the methods recommended by JEDEC. At the board level, several studies have shown that the SMT reflow process is, in general, beneficial for whisker mitigation as compared to loose components. Nonetheless, the effects of various assembly parameters, such as the reflow temperature or paste volume, are not fully investigated. To better understand the effects of assembly process on whisker growth propensity, JESD-201 tin whisker thermal cycling testing was performed on both SnPb and SnAgCu assemblies manufactured with components from multiple suppliers, various reflow temperatures, and different paste volumes.

The experimental results indicate that the SMT assembly process generally reduces the occurrence of tin whiskers in comparison to the loose components. This reduction in occurrence is most noticeable in SAC assemblies. For SnPb assemblies only, the reflow temperature effect is notable but the paste volume effect is minor. Sporadically, long whiskers are found in both SnPb and SAC assemblies. This observation suggests that the board assembly process is not always effective in mitigating whisker risk, especially in consideration to the maximum tin whisker length. Therefore, it is always critical to select components with acceptable tin whisker test result per JESD-201, coupled with board level testing for the verification purposes.

Key words: Pb-free, tin whisker, assembly, reliability, risk assessment, thermal cycling

Introduction

In recent years, the implementation of RoHS Directive [1] has driven the majority of the electronic industry to transition to Pb-free components and Pb-free assembly process for electronic system manufacturing. However, certain high-reliability products, such as network infrastructure equipment, military applications, and medical devices continue to utilize SnPb solder, permitted by RoHS Directive, due to potential reliability concerns. One of the concerns is the spontaneous growth of tin whiskers from tin-plated component finishes. These thin, conductive filaments have length as long as several hundred microns for the commonly used matte tin

finishes, and over 1 mm for bright tin finishes. There are many documented cases where the failures were caused by tin whiskers [2].

It is frequently reasoned that SnPb solder paste would reduce the tin whisker risk due to the presence of Pb on the solder joints and the effectiveness of Pb in mitigating whisker growth at a very low (0.5 to 2%) concentration level [3, 4]. Moreover, it is argued that no increase of failures had been observed since many Pb-free components were introduced to the market place (~ late 1990s), long before the RoHS Directive implementation. Previously, several studies [5, 6] have investigated the effect of assembly process on tin whisker growth propensity in response to thermal cycling. The results

seem to indicate that SnPb (or SnPbAg) assembly process does slightly better in reducing the maximum whisker length. However, the test components used in these studies were from only one manufacturer and the sample size was too small (5 to 6 pieces each condition) to provide a statistically significant conclusion that is applicable to the standard SMT manufacturing process in a production scale.

This study is aimed to re-examine the tin whisker mitigation effects of SnPb and Pb-free (SAC) solder pastes statistically, as well as identify critical assembly process parameters to minimize tin whisker risk in order to maintain product reliability as the Pb-free transition takes place. In addition, the dependencies between assembled component tin whisker growth propensity and the loose component quality are also investigated to understand the effectiveness and necessity of component level tin whisker testing.

In order to assess the risk in a consistent manner, it is expressed as the combined effect of the probability (occurrence) of an event and the impact (severity) of such event, should it occur:

Risk = Probability (occurrence) * Impact (severity)

For this study, probability was determined based on the fraction of components with tin whiskers observed after testing. A smaller percentage of components with tin whiskers would indicate a better mitigation effect. The impact or severity was evaluated by the maximum length of whiskers observed on each component. As the whisker length increases, the impact may increase from zero to bridging adjacent pins or various nearby components, or potentially interfering high frequency signals [7].

Experimental

Sample selection and test assembly preparation

Leadframe components from multiple suppliers were selected to represent the *Known Good Parts (KGPs)* and *Known Bad Parts (KBPs)* based on the JESD-201 tin whisker test results provided by the suppliers. The package types, leadframe materials, plating finishes, and test results from the suppliers and this study are listed in Table 1. Two Cu leadframe components were included in the matrix as references in case other dominant factors in addition to CTE mismatch were observed. Note that one of the Cu leadframe components utilized NiPdAu plating. The purpose was to incorporate a reference to isolate any tin whisker growth directly related to the solder pastes. All components were commercially available and functional parts procured in their original packages.

These components were assembled using standard automatic SMT process with two SnPb solder pastes (one aqua-clean, and one no-clean) and six different Pb-free solder pastes (two aqua-clean, and four no-clean) of which the composition was Sn-3.0Ag-0.5Cu (SAC305). For each metallurgy (SnPb vs. SAC), three reflow peak temperatures were used with the profiles tuned to meet the process parameter recommendations by the paste suppliers. The solder paste volume was varied by using two stencil thicknesses (5 and 6 mil) and three different opening sizes. The “nominal” paste volume variations relative to the standard paste volume (90% opening relative to pad size and 5 mil thickness) were -20%, -10%, 0% (i.e. standard volume), 10%, 20% and 30%. The effects of solder paste metallurgy, reflow temperature difference, as well as the solder paste volume will be discussed.

Table 1: Component selection and component level (i.e. loose parts) test results from suppliers and this study

	Supplier	Package Type	Leadframe Material	Plating Finish	Loose Component JESD-201 TC Test Results			
					Supplier Report	This study		
						No. of parts tested (pcs)	Occurrence	Max length (um)
Known Bad Parts (KBPs)	A	SOT23 3L	A42	Matte Sn	Fail	126	98%	80
	B	TSSOP-II 66L	A42	Matte Sn	Fail	42	100%	170
	C	TSSOP-II 66L	A42	Matte Sn	Fail	42	100%	150
Known Good Parts (KGPs)	D	SOT23 3L	A42	Matte Sn	Pass	126	100%	50
	E	SOT363 6L	A42	Matte Sn	Pass	126	87%	90
	F	TSSOP-II 66L	A42	SnBi	Pass	42	100%	180
	G	TSOP 44L	Cu	Matte Sn	Pass			
	H	TSSOP-II 56L	Cu	NiPdAu	N/A			

Test and Inspection Method

The assembled test boards and the loose components (after simulated reflow) were subjected to the standard JESD-201 thermal cycling test condition at -55°C to 85°C, 3 cycles/hr, 10 minute soak for 1500 cycles. At each readpoint (0, 500, 1000, 1500 cycles), 1/4 of the test boards and loose components were removed from the test chamber for inspection. These removed test samples were preserved for other studies, therefore not returned to the chamber for further testing. All component leads were inspected with a 67x optical microscope. If whisker growth was observed on a component, the length of the longest whisker on the component was recorded. Since this data recording method only documented the longest whisker on each component, it inevitably introduced data bias or skewness towards the long side of the commonly observed “lognormal” distribution of tin whisker length [8]. SEM and EDX on selected tin whiskers were performed to obtain more details on their shapes and locations.

Results and Discussion:

Known Good Part vs. Known Bad Part

To build a solid foundation for understanding the mitigation effect of the assembly process, it is important to first evaluate the loose component performance after thermal cycling testing. As shown in Table 1, 87 to 100% of the loose components grew whiskers and all failed the JESD-201 acceptance criteria regardless the component was originally considered a KGP or KBP. This test result is different from the supplier reported results, and the discrepancy may be due to (1) plating quality lot-to-lot variation, or (2) test condition differences, such as temperature range (-40 to 85°C used by previous studies and many suppliers vs. -55 to 85°C used for this study, both are allowed by JESD-201 [9]), dwell time, ramp rate, etc. In this case, it is possible that the excess stress exerted by the large thermal cycle range, -55 to 85°C, may have overshadowed the tin whisker growth propensity difference between the KGPs and KBPs.

On the other hand, once the components were assembled, all KGPs (2096 pieces A42 leadframe parts, and 384 pieces Cu leadframe parts) passed JESD-201 acceptance criteria regardless of the assembly parameters whereas the KBPs (1824 pieces A42 leadframe parts) demonstrated various degree of whisker growth depending on the specific assembly parameters and the manufacturers. This

observation confirms that the first and foremost important aspect of tin whisker risk mitigation is to implement component level tin whisker test and use only parts that meet JESD-201 acceptance criteria. Since all the KGPs have passed the JESD-201 test, the rest of the data analysis and discussion will be focused on the mitigation effects on the KBPs.

SnPb vs. SAC Solder Pastes

As the industry is transitioning to Pb-free manufacturing, it is critical to evaluate quantitatively if tin whisker risk would increase as a result of the removal of Pb. Contrary to common beliefs and results from previous studies, this study shows that SAC solder pastes seem more effective in suppressing the occurrence of tin whiskers (Figure 1). Only 1% of the tested KBPs grew whiskers with a length exceeding the JESD-201 acceptance criteria. Nonetheless, the SAC assembly process does not seem to reduce the severity of tin whisker risk since the maximum whisker length in SAC assemblies is still excessively long (~ 200um), and comparable with the loose component test result.

In order to assess the statistical significance of the solder paste metallurgy on the maximum tin whisker length, we analyzed the non-zero maximum whisker lengths using a lognormal distribution as shown in Figure 2. The Normal Quantile Plot shows that the maximum tin whisker length of both SnPb and SAC assemblies follow the lognormal

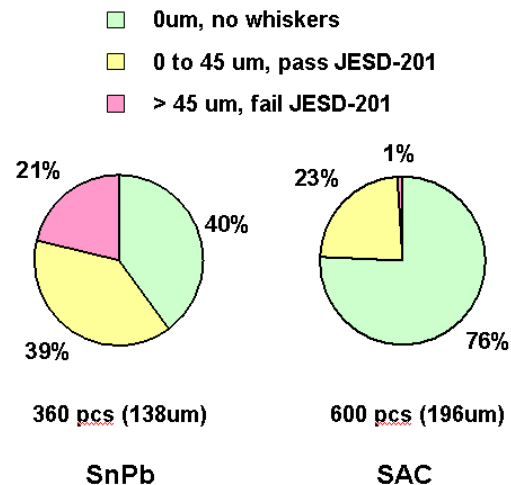


Figure 1 Comparison of tin whisker occurrence and maximum length distribution in the SnPb and SAC assemblies. Total number of KBPs tested and the longest whisker length for each metallurgy are listed below the pie charts. The percentage indicates the fraction of components in each of the three whisker length categories

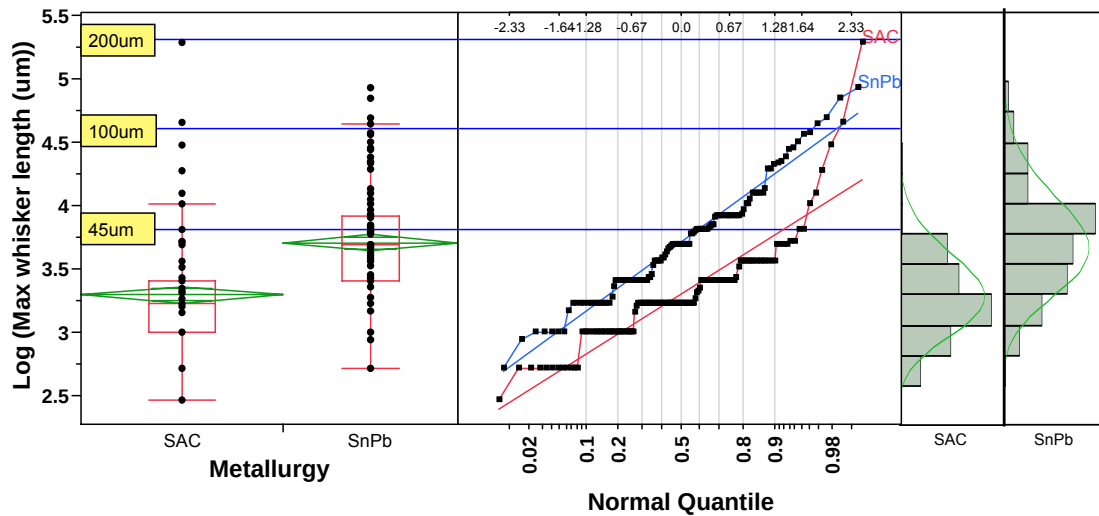


Figure 2 Maximum whisker length comparison between SnPb and SAC assemblies. The blue horizontal lines indicate the length in linear scale. The curves in the histograms are the fitted normal distribution function.

distribution relatively well until approximately 90 to 95 percentile, with the deviation most noticeable for SAC assemblies. The mean diamonds and box plots also show that the tin whisker length distribution in SnPb assemblies follows the lognormal distribution more closely. Statistically speaking, tin whiskers observed in SAC assemblies are shorter in average. In summary, due to the reduction in occurrence of tin whiskers and the maximum whisker length, it may be reasonable to propose that SAC assembly process in general achieves better tin whisker mitigation effect. Nonetheless, the outliers with excessive length still remain a concern.

It is worth noting that certain amount of kurtosis and skewness was introduced to the true whisker length distribution as a result of the method used to record the measurements for the large test sample size. Because the data recording method disregarded all except the longest whisker on each component, it skewed the population to the longer side of the distribution. In practice, this skewness helps to account for the longer tin whiskers which are most likely to cause failures although the goodness of fit to the lognormal distribution function is reduced.

Component Plating Quality Dependence

A closer look at the whiskers found on the SAC assemblies by the manufacturers revealed that tin whisker growth on the KBPs from Supplier B was completely mitigated by the assembly process, while approximately 1/3 of Supplier A components still grew whiskers with the maximum whisker length close to 200 μm (Figure 3). The performance of Supplier C components was somewhat in the middle where the tin whisker occurrence was reduced

considerably with shorter maximum whisker length but the statistical significance of tin whisker length difference between Supplier A and C was negligible (Figure 4).

In the meantime, the three longest whiskers in SAC assemblies were found to be from Supplier A. The SEM inspections in Figure 5 show that they grew out of the dam bar area except that the longest one geminated from the front of the lead where solder coverage was confirmed by SEM/EDX. The dam bar area whisker growth was not driven by corrosion as commonly observed on Cu leadframe components under high temperature/high humidity storage test condition [10] since the leadframe material was A42 and the test condition did not utilize excess humidity. The exact growth mechanisms for these whiskers are under investigation.

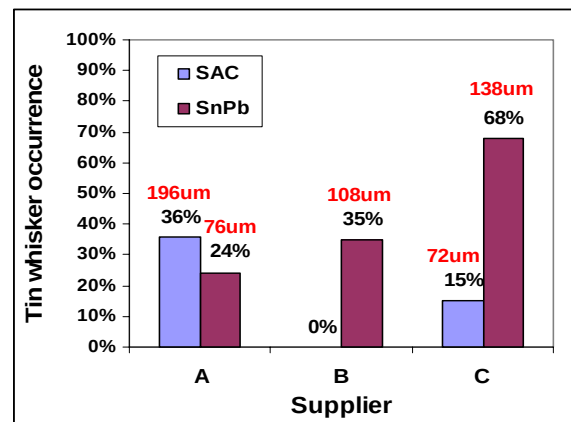


Figure 3 Tin whisker occurrence and maximum whisker length in SnPb and SAC assemblies by supplier.

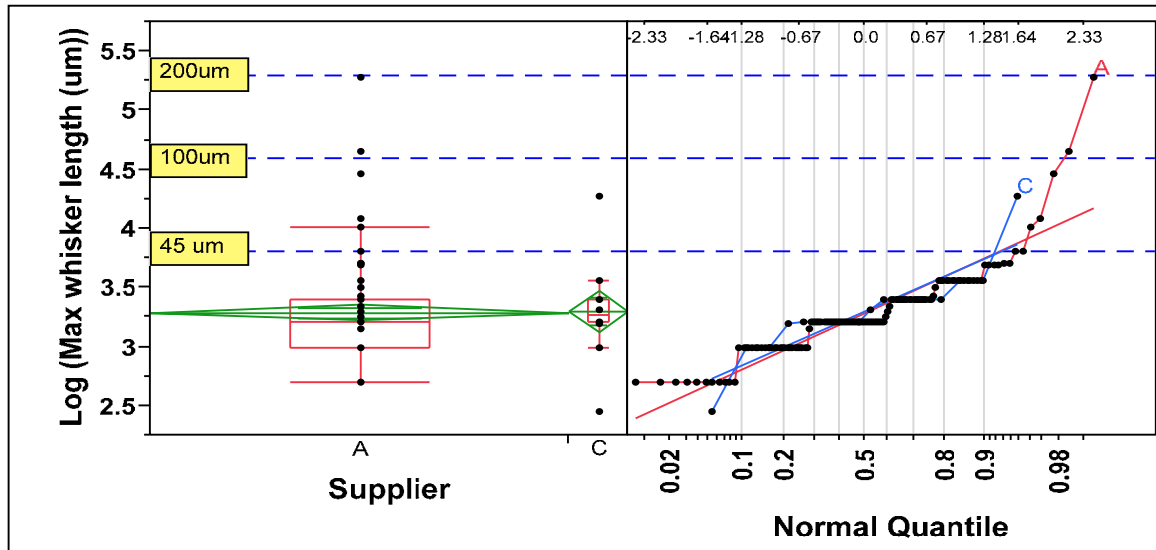


Figure 4 Maximum tin whisker length comparison in SAC assemblies by supplier. Note that most of the long whiskers exceeding 45um were from Supplier A.

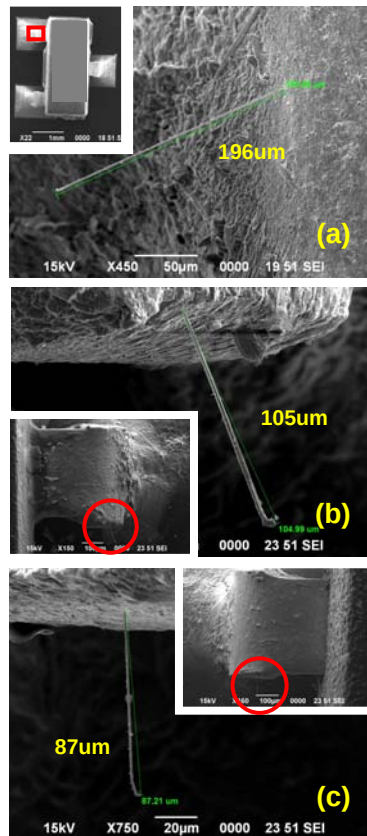


Figure 5 SEM images of the three longest whiskers found on SAC assemblies. All three whiskers were from Supplier A. (a) Tin whisker grew from the front of a lead. (b) and (c) Tin whiskers grew out from the dam bar areas.

For SnPb assemblies, the occurrence of tin whiskers was reduced for all three suppliers yet the mitigation effect was not as pronounced as that in the SAC assemblies (Figure 3). Moreover, the relative ranking of the three suppliers based on the occurrence in SnPb assemblies was different from which in SAC assemblies. It suggests that the assembly process mitigation effectiveness is associated with the interaction between the solder paste and the original plating finish quality. The whisker length analysis (Figure 6) shows that the mean maximum whisker length from Supplier A is statistically smaller than that from Supplier B and C, while Suppliers B and C components have statistically comparable whisker lengths in SnPb assemblies.

Reflow Peak Temperature Dependence

For both SnPb and SAC solder pastes, three different reflow peak temperatures were used to manufacture the test boards. The significance of the temperature dependence is examined by using the non-parametric Kruskal-Wallis H-test. The result suggests that the reflow peak temperature does not affect the tin whisker growth significantly (p value = 0.43) in SAC assemblies. This finding is consistent with the observation from the occurrence pie charts in Figure 7, where all three reflow peak temperatures were equally effective in suppressing tin whisker growth in more than 70% of the KBPs. Only 1-2% of the components grew whiskers longer than 45um.

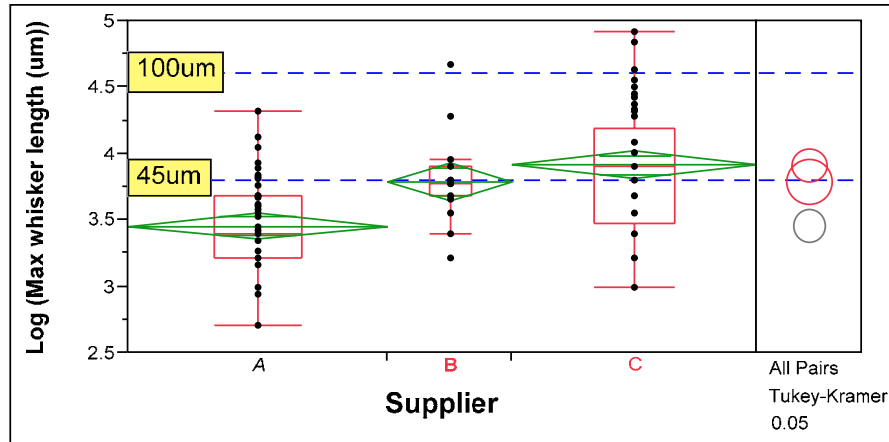


Figure 6 Maximum tin whisker length comparison in SnPb assemblies by supplier.

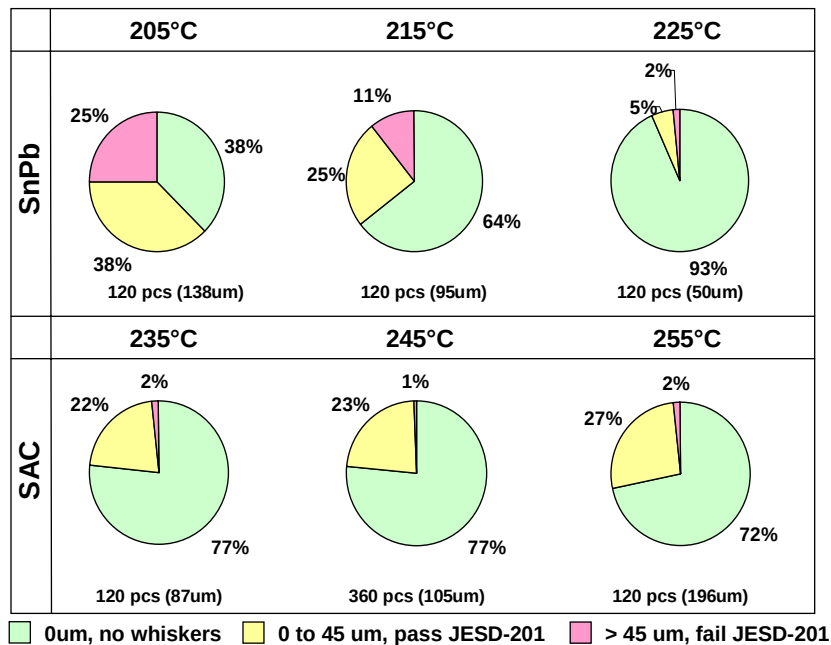


Figure 7 Tin whisker occurrence at different reflow peak temperature for SnPb and SAC assemblies. The total number of KBPs tested and the maximum tin whisker length for each condition are listed below the corresponding pie chart.

Conversely, the Kruskal-Wallis test found that the reflow peak temperature played a prominent role in the mitigation effectiveness in SnPb assemblies (p value < 0.001). As the reflow peak temperature was increased, the occurrence of tin whiskers was reduced (Figure 7). The reason may be due to improved solder coverage at higher reflow temperature and more adequate mixing between the SnPb solder and the partially molten surface finish (melting point of pure Sn is 232°C). In addition, the reflow process also serves to release the initial stress stored in the plating finishes after the trim and form operations. As for the maximum whisker length,

further analysis shows that although the reflow peak temperature affected the whisker occurrence significantly, it did not have significant impact on the tin whisker length distribution (Figure 8).

Solder Paste Volume Dependence

The solder paste volume dependence in SnPb and SAC assemblies was also analyzed. The Kruskal-Wallis H-test results show that paste volume has a statistically significant role in suppressing whisker growth in SnPb assemblies (p value < 0.01), while there is no effect in SAC assemblies (p value =

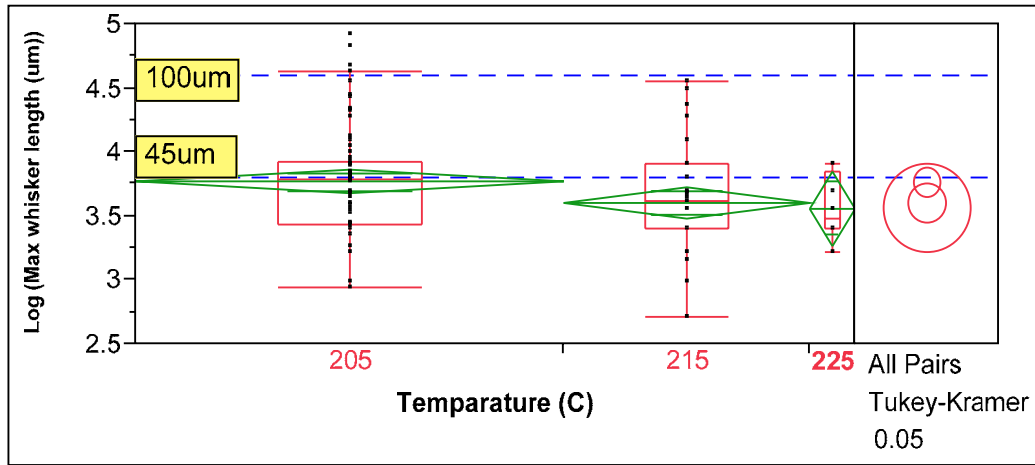


Figure 8 Maximum tin whisker length comparison in SnPb assemblies by reflow peak temperature.

0.2962). Figure 9 shows that in SnPb assemblies, the whisker occurrence decreased in general as the solder paste volume was increased from 20% underprint (vs. standard volume) to 30% overprint. This effect appears to be most noticeable for 205 and 215°C assemblies. For the assemblies reflowed at 225°C, the standard paste volume was adequate to reduce the whisker occurrence to less than 10%. In the tin whisker occurrence plot for SAC assemblies (Figure 10), no clear volume dependence was found. This observation is consistent with the Kruskal-Wallis H-test result.

Combining this weak paste volume dependence with the reflow peak temperature effect discussed earlier, it is logical to conclude that solder paste volume effect is only secondary. From the manufacturing point of view, it is a parameter that can have adverse consequences because it increases the possibility of solder joint bridging as well as changes the solder fillet shape and joint strength.

Conclusion

This study investigated a wide range of material and process parameters that may influence the tin whisker risk in board assemblies. Because the sample size is sufficiently large, statistical analysis was performed to identify the significance of each parameter for practical application in a manufacturing environment. Key findings from this study are:

- Component level tin whisker testing is critical to achieve high quality plating finishes that are more resistant to tin whisker growth. This study shows that KGPs performed as expected (all passed JESD-201 acceptance criteria) after assembly, regardless of the solder paste metallurgy. Suppliers are encouraged to

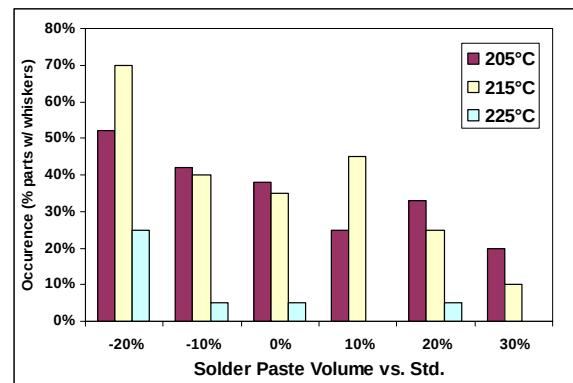


Figure 9 Tin whisker occurrence comparison by solder paste volume at different reflow peak temperature in SnPb assemblies.

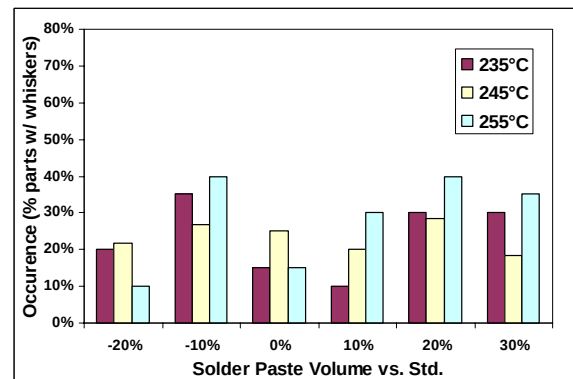


Figure 10 Tin whisker occurrence comparison by solder paste volume at different reflow peak temperature in SAC assemblies.

perform JESD-201 tests as part of the ongoing OA/QC program. It is highly recommended for OEM/ODMs to procure components meeting JESD-201 acceptance criteria to minimize tin whisker risk at the board level.

- Compared to SnPb solder paste, SAC paste is more effective in mitigating tin whisker risk as evidenced by a notable reduction in tin whisker occurrence. This observation is in sharp contrast with conventional thinking and previous study results. One explanation is that SAC solder wets the component lead surfaces better [6], therefore provides better solder coverage. Additionally, the higher reflow temperature of SAC allows the surface Sn finish to fully melt and mix with the solder paste, and release the stress. For SnPb paste, the lower reflow temperature may not allow sufficient Pb to be incorporated into the plating finish and achieve the desired degree of mitigation effect.
- Although the assembly process is effective in reducing tin whisker occurrence, the maximum whisker length in either SnPb or SAC assemblies is found to be comparable with that observed on loose components, therefore still remains a reliability concern. As it has been highlighted previously, this finding demonstrates that component quality is the most dominant factor on board level tin whisker growth propensity.
- The reflow peak temperature plays a significant role in tin whisker mitigating in SnPb assemblies. Higher reflow peak temperature significantly reduces the occurrence of tin whiskers. As discussed earlier, this effect may be explained by better solder coverage and mixing achieved at higher reflow temperature.
- Solder paste volume has minor effects on tin whisker mitigation. For KBPs that need to be soldered at the lower end of the SnPb process window, increased solder paste volume results in noticeable reduction of tin whisker occurrence. However, this practice may increase the risk of solder joint bridging.
- This study shows that the overall effectiveness ranking of the key parameters is: Component quality > Solder paste metallurgy > Reflow peak temperature > Solder paste volume.

2003 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment," *Official J. Eur. Union*, pp. L37/19–L37/23, Feb. 13, 2003. Available: http://europa.eu.int/eurlex/pri/en/oj/dat/2003/l_037/l_03720030213en00190023.pdf

2. H. Leidecker and J. Brusse, "Tin whiskers: A history of documented electrical system failures—A briefing," Space Shuttle Program Office, 2006. Available: http://nepp.nasa.gov/whisker/reference/tech_papers/2006-Leidecker-Tin-Whisker-Failures.pdf
3. S. M. Arnold, "Repressing the Growth of Tin Whiskers", *Plating Magazine*, Jan. 1966;
4. P.L. Key, "Surface Morphology of Whisker Crystals of Tin, Zinc and Cadmium," *IEEE Electronic Components Conference*, pp.155-157, May, 1970.
5. P. Oberndorff, M. Dittes, and P. Crema, "Whisker Testing: Reality or Fiction" *Proc. of IPC/Soldertec 2nd International Conference on Lead Free Electronics "Towards Implementation of the RoHS Directive"*, June 2004, Amsterdam, the Netherlands. Available: <http://www.st.com/stonline/leadfree/testing.pdf>
6. Greg Henshall, V. Schroeder, N. Hancock, J. Ortkiese, and A. Saxberg, "Impact of 2ndLevel Board Assembly on Tin Whisker Growth for Alloy 42 TSOPs Subjected to Thermal Cycling", *iNEMI Tin Whisker Workshop at ECTC*, May 2006, San Diego, CA.
7. G.T. Galyon and R. Gedney, "Avoiding Tin Whisker Reliability Problems", *Circuits Assembly*, pp.26-31, August, 2004.
8. Y. Fukuda, M. Osterman, and M. Pecht, "Length Distribution Analysis for Tin Whisker Growth", *IEEE Transactions on Electronics Packaging Manufacturing*, 30(1): 36-40, 2007.
9. JEDEC standard JESD-201, "Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes" March, 2006. Available: <http://www.jedec.org>
10. P. Su, J. Howell, and S. Chopin, "A Statistical Study of Sn Whisker Population and Growth during Elevated Temperature and Humidity Tests", *IEEE Transactions on Electronics Packaging Manufacturing*, 29(4): 246-251, 2006.

References

1. Directive 2002/95/EC/ of the European Parliament and of the Council of 27 January