The Effect of Temperature Cycling on Tin Whisker Formation

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Abstract
Tin platings on component finishes may grow whiskers under certain conditions, which may cause failures in electronic equipment. Although the thermal mismatch of tin and FeNi42 is well known and tin whiskers have been reported after thermal cycling of this material combination, no systematic investigation on the effects of thermal cycling is available. In this paper we describe the influence of various cycling conditions on the whisker growth rate of tin on FeNi42 and attempt to correlate these tests to service life conditions. We demonstrate that the whisker length has a linear relationship with ΔT. In addition, the whisker growth rate appears to decay as a function of number of cycles and/or whisker length. Furthermore, the maximum whisker lengths appear to be reduced on plated components that have been assembled to a printed circuit board.

Introduction
Recent activities of component manufacturers to introduce electroplated, pure tin as the lead-free alternative to SnPb plating for the solderable finish on leadframe-based devices draws new attention to the well known phenomenon of whisker growth. Since most components have copper-based leadframes much effort has been put into investigations of tin whiskers formed on copper-based materials[1,2,3,4,5]. A mechanism has been proposed for tin whisker growth on copper-based materials and viable countermeasures have been identified[6,7]. For tin electroplating on copper-based materials, the focus has been on isothermal storage conditions in order to investigate the propensity for whisker growth during storage in distribution centers or at the end customer before assembly. It is believed that second level assembly will slow the process of whisker formation and growth.

Although tin plated copper leadframes tend to grow whiskers under isothermal storage conditions, matt tin plated FeNi42 leadframes do not typically grow whiskers under these circumstances. FeNi42 leadframes are not as popular as Cu-based leadframes, but they are still widely used in the electronics industry. In temperature cycling, tin electroplate on FeNi42 typically forms whiskers, while tin plated copper typically exhibits minimal whisker growth during temperature cycling. The explanation for this different behaviour is presumably related to different mechanisms of stress induction[6]. For tin plated on copper, it is believed that compressive stress is formed in tin finishes due to the excessive irregular growth of the intermetallic Cu_6Sn_5 at the copper-tin interface. On the other hand, for tin plated on FeNi42, stress may be induced by the large mismatch of the coefficients of thermal expansion between FeNi42 (cte = $4.3 \cdot 10^{-6}\ K^{-1}$) and tin (cte = $23 \cdot 10^{-6}\ K^{-1}$). This mismatch can cause stress in the constrained tin layer, when temperature cycling is applied.

Since temperature cycles due to the environment or operation occur during the service life of most electronic equipment, the risk of failure caused by whisker growth on tin plated FeNi42 based components should be investigated. Further, it must not be assumed that all of the tin plating fuses during the board assembly processes, so portions of the as-electroplated finish will still exist during operation.

Based on some experimental findings and the above considerations, the current study was initiated to address the various parameters that influence whisker growth in tin electroplated on FeNi42.

Experimental
The test packages used for the experiments were fully processed TSOPII-66 with a memory chip inside. All packages are from the same production lot and are electroplated in the standard conditions for mass production. The thickness of the tin finish has been measured by X-ray fluorescence analysis as 8.5 ± 0.1 µm. The tin finish is characterised as a matt pure tin finish with an average grain size of 2 µm to 6 µm. The electrolyte for the electroplating process was an MSA-based chemistry of the latest generation. The plating process was performed in a continuously operating belt line.

SnPb plated components of same type were plated and used as a control. These Sn-Pb parts have also been made during standard production and underwent the same conditions of temperature cycling and inspection as described below. The plating thickness for the SnPb control group was 8.2 ± 0.1 µm and the lead content was 10 ± 1 %.

For every test condition and test interval (e.g. 250, 500, 1000 cycles), five components of both plating types have been evaluated. Thus 330 leads are inspected for each environmental condition and test interval Hence – if not explicitly mentioned – 5 different components have been inspected for every data point in the diagrams.

Three types of temperature cycling chambers have been used to apply the various conditions. In most cases with so called air to air or liquid to liquid shock conditions a two chamber system was used, so that the transfer from the hot to the cold chamber and vice versa occurs within a few seconds. The dwell time began with the completed transfer of the components from one to the other chamber. Temperature cycles of less than 10 K/min ramp rate have been performed by the use of single chamber systems. Due to the limited thermal mass of the components the test samples followed directly the temperature of the chamber and dwell time started after reaching the temperature limit with a tolerance of 5 °C.

Inspection has at first been done with an optical microscope at a magnification of 50x. This method was chosen because many leads can be evaluated quickly, unlike in SEM, and the whisker lengths measured with an optical microscope are consistent with whisker lengths measured in SEM. Thus every lead was fully inspected in live bug position and the longest whisker identified. After noting the position of the longest whisker every component was inspected in scanning electron microscope (SEM) and a picture taken from the longest whisker of every component at 1000x magnification. The length of these whiskers have been measured in SEM again for comparative reasons and for higher accuracy. A maximum whisker length for a particular environmental condition and test condition is calculated by averaging the maximum whisker length measured on each of the 5 components exposed to the same condition.

Additionally pictures of the area without influence of trim & form tools or any bending and from the tip of the leads at 300 x magnification were taken to get an overall impression of the whisker density and the length distribution.

During the design phase the parameters of influence have been identified as

- the temperature range
- the absolute temperature
- the ramp rate
- the dwell time.

In addition to evaluations of individual components, SnPb-soldered and SnAgCu-soldered modules have undergone temperature cycle testing to study the effect of second level assembly on whisker formation. The reflow profiles were typically of SnPb and SnAgCu assembly and peak temperatures were set as 215 °C and 245 °C, respectively. The details of cycling conditions can be derived from Table 1.

For comparative reasons, tin plated copper has undergone 500 temperature cycles from –40 °C to 125 °C in an air to air shock experiment with 20 min dwell time in an earlier experiment. At that time the same conditions were applied to a tin plated FeNi42 control group.

Table 1 - Temperature cycling conditions

<table>
<tr><th>Temperature in °C</th><th>Type / ramp rate in K/min</th><th>Dwell time in min</th><th>Number of cycles</th><th>Comment</th></tr>
<tr><td colspan="5">Cycle conditions for components only</td></tr>
<tr><td>-40 / +85</td><td rowspan="6">Air to air shock</td><td rowspan="8">10</td><td rowspan="6">250, 500, 1000,1500,2000, (2500)</td><td rowspan="4">Various T-range, upper limit constant</td></tr>
<tr><td>-15 / +85</td></tr>
<tr><td>+15 / +85</td></tr>
<tr><td>+45 / +85</td></tr>
<tr><td>0 / +125</td><td rowspan="2">Various absolute T, T- range constant</td></tr>
<tr><td>+50 / +175</td></tr>
<tr><td>-40 / +85</td><td>Liquid to liquid</td><td rowspan="8">500</td><td rowspan="2">Various ramp rate</td></tr>
<tr><td>-40 / +85</td><td>1</td></tr>
<tr><td>-40 / +85</td><td rowspan="6">Air to air shock</td><td>5</td><td rowspan="2">Various dwell time</td></tr>
<tr><td>-40 / +85</td><td>20</td></tr>
<tr><td>-40 / +125</td><td rowspan="4">10</td><td>Reference Sony</td></tr>
<tr><td>-55 / +45</td><td rowspan="3">Various T-range, lower limit nearly constant, (65 / +150 automotive)</td></tr>
<tr><td>-55 / +85</td></tr>
<tr><td>-65 / +150</td></tr>
<tr><td colspan="5">Cycle conditions applied to components and modules</td></tr>
<tr><td>-40 / +85</td><td>5</td><td>30</td><td>250, 500, 1000</td><td></td></tr>
<tr><td>0 / +125</td><td>Air to air shock</td><td>20</td><td>1000</td><td>Standard qualification</td></tr>
</table>

Results and Discussion

Tin whiskers on copper vs. alloy 42

The comparison of tin-plated FeNi42 (alloy 42) and tin-plated copper confirms the different whisker growth behaviour of tin plated on the two materials, as shown in Figure 1. In this particular thermal cycling experiment (Figure 1), whiskers grew on FeNi42, but whiskers did not grow on the copper-based leadframe. Clearly, thermal cycling causes whisker growth in tin plated on alloy 42. Thermal cycling may not affect tin plated on copper for one of two reasons. First, the thermal mismatch between tin and copper is not large. Second, the high upper limit (125 °C) in the temperature cycling may prevent irregular growth of Cu-Sn intermetallics that have been correlated with whisker growth in tin plated on copper at lower temperatures[6,8]. At 125 °C, the bulk diffusion mechanism is already predominant for copper atoms to diffuse in to the tin matrix rather than preferential diffusion in the tin grain boundaries. Thus a dense layer of Cu-Sn intermetallics may be formed at the interface at 125 °C, which could prevent further irregular growth of intermetallics, thereby suppressing stress induction. Only a slight cracking of the tin grains can be observed, which is not as significant as the "disruption" on FeNi42.

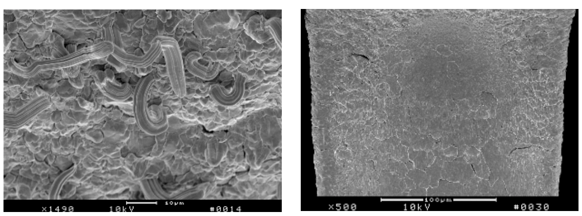

Figure 1 – Whisker grown on tin plated FeNi42 (left) after 500 TC –40/+125. No whiskers on tin plated Cu (right).

Thermal cycling of tin plated alloy 42

In Figure 2, a representative image of tin whisker formation on a tin-plated FeNi42 lead is presented. Images like that in Figure 2 were collected for every measurement plotted in Figure 3 to Figure 8. In fact, each plotted value is the average of the longest whisker per component. In most figures, the respective standard deviation from the five components evaluated at each test condition is plotted as well. It must be generally noted that these longest whiskers grow very sporadically, whereas the rest of the surface is covered with significantly smaller whiskers. For instance after 1000 cycles of -40 °C to +85 °C cycling (Figure 2), the longest whiskers were approximately 62 µm, but the median length whiskers were approximately 20 µm. These smaller whiskers continued to increase in length with additional thermal cycling.

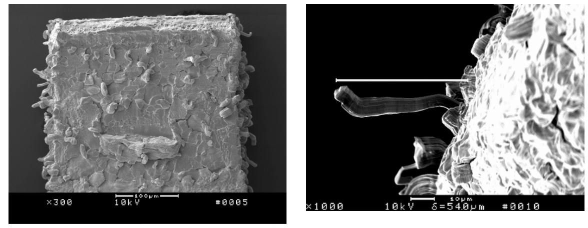

Figure 2– Examples of overview of lead tip (left) and longest whisker of a component (right). Both after 1000 cycles air to air shock, -40 °C / +85 °C, 10 min dwell.

Thermal cycles with a constant T_{max} and varied ΔT

From Figure 3, it is apparent that whisker lengths increase with the number of cycles. However, the rate of whisker growth appears to decrease over time. For each thermal cycling temperature range, the whisker growth rate slows after 250 cycles. In some cases, the whisker growth rate appears to continue to slow above 250 cycles. Generally a parabolic relationship between whisker length and the number of thermal cycles may be appropriate.

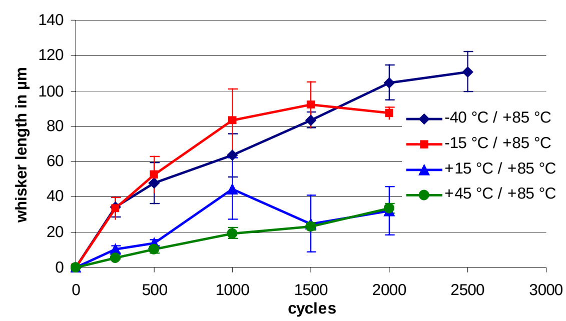

Figure 3 – Whisker growth vs. Number of cycles. Air to air shock cycling, 10 min dwell time, upper limit constant (the data with 1500, 2000 and 2500 cycles for –40 °C / +85 °C have been derived from the same samples)

As shown in Figure 3, in addition to the dependence of whisker growth rate on the number of cycles, there is a dependence on the temperature range of the thermal cycles. Typically there is a trend that the whisker growth rate per cycle increases with increasing temperature range (this will be discussed again in Figure 5). In addition, for the -40 °C / +85 °C and -15 °C / +85 °C cycling, a decay of the growth rate can be observed, which starts at 1000 cycles for the latter condition and 2000 cycles for the former. Aside from the decay point, the -40 °C to +85 °C and the -15 °C to +85 °C data are similar.

Based on these two sets of data, temperatures below -15 °C appear to have little influence on the whisker growth rate, but may influence the number of cycles at which the growth rate decays. A possible explanation for the similar behaviour is: The whisker formation is a diffusion-controlled process and thus significantly dependent on the homologous temperature of the material. At low temperatures the whisker growth is quite limited. Furthermore it must be kept in mind that compressive stress is induced in the tin layer when ramping up from low to high temperatures. Vice versa a tensile stress is induced when ramping down. Due to also limited stress relief by annealing (creep) at low temperatures, especially at short dwell times, this tensile stress is still effective before ramping up again. Thus some fraction of the stress will simply be stored elastically and released when heating up again. Hence the elastically stored stress will not contribute to whisker growth. If the temperature for the lower dwell is higher (significantly above –15 °C) or the dwell time longer, the tensile stress will be relieved by annealing during dwell. At some point in the thermal cycle range, there should be a point of zero stress. If tensile stress is not relaxed during the lower temperature dwell, then this zero point will remain approximately constant during cycling (elastically reversed) and will not be affected by the exact temperature of the lower limit. At higher temperatures, still below the zero point, the tensile stress will be partially or fully relieved during the dwell, thereby shifting the zero point to a lower temperature in the thermal cycle range. If this zero point is equivalent with the lower temperature limit of the temperature cycle (due to long dwell time or moderate lower limit) every increase of temperature after dwell at the lower limit will result in compressive stress, acting as the driving force for whisker growth.

There are two other features of the data in Figure 3 that may be notable. First, the exceptionally high value for whisker length after 1000 cycles of +15 °C / +85 °C is an example of the randomness in the formation of a long whisker from lead-to-lead and part-to-part. Second, the +15 °C to +85 °C and the +45 °C to +85 °C data are fairly similar. A physical/ metallurgical explanation for this behaviour is not apparent. However, we have to acknowledge that determination and measurement of the longest whisker is not a methodical procedure and the sporadic growth of long whiskers may not be a sufficient statistical sampling.

Thermal cycles with a constant T_{min} and varied ΔT

In Figure 3, the temperature range of the thermal cycles was varied while holding the peak temperature constant. Conversely, in Figure 4, the minimum temperature of the thermal cycles is held approximately constant and the peak temperature is varied. Generally the trend towards higher growth rates at larger temperature intervals is confirmed. The data taken at a peak temperature of +150 °C shows rapid whisker growth without obvious annealing effect expected at higher peak temperatures. The data from Figure 3 and Figure 4 have been included in Figure 5, which compiles whisker lengths as a function of thermal cycle range.

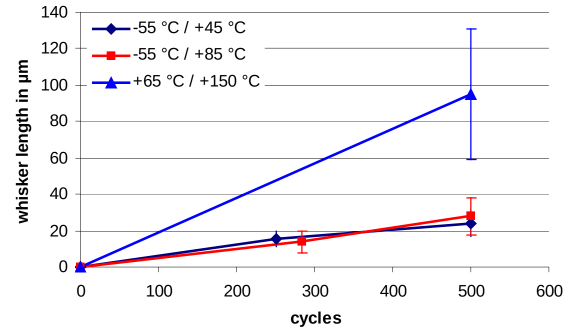

Figure 4– Whisker growth vs. number of cycles. Air to air shock, 10 min dwell time, lower limit nearly constant

Dependence of whisker length on ΔT

In the previous section, it was shown that temperatures below -15 °C have a negligible contribution to whisker growth at the dwell times reported in this paper. Figure 5 shows a whisker length vs ΔT plot, where temperatures below -15 °C have been neglected. The linear relationship of the whisker length from ΔT in the respective temperature range is more apparent particularly for the data taken after 250 and 500 thermal cycles.

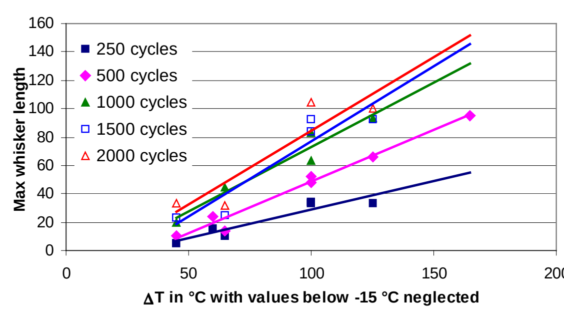

Figure 5 – Maximum Whisker length vs. ΔT, air to air shock cycling, 10 min dwell

Thermal cycles with a constant ΔT

As shown in Figure 6, comparing the variation of the absolute temperature range at constant ΔT it appears that a higher peak temperature lead to faster initial growth of the whiskers between 250 and 1000 cycles. However, above 1000 cycles, the high temperature cycling (0 °C and +125 °C) leads to significant decay of the growth rate. A decay in growth rate at 1000 cycles was also observed for the -15 °C to +85 °C data presented in Figure 3. A similar decay may occur for the parts cycling from -40 °C to +85 °C above 2000 cycles. This decay of the growth rate may mark an upper limit for the whisker formation and growth.

There are a few physical reasons to explain the decay in whisker growth. After 1000-2000 cycles the whisker density is very high. Most of the surface is covered by small protrusions. Additionally the surface shows an extensive intergranular cracking. It can be assumed that the development of stress will be significantly hampered, if the plating layer is crossed by deep cracks that isolate whiskers from the surrounding tin plating.

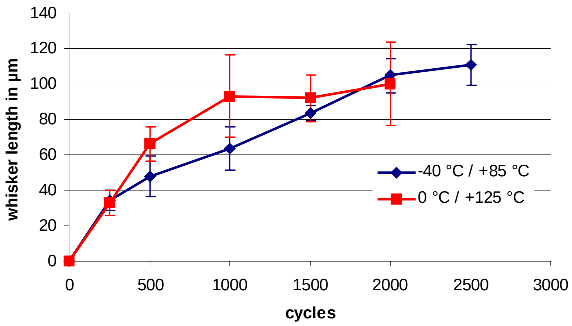

Figure 6 – Whisker growth vs. number of cycles. Air to air shock, 10 min dwell time, various absolute temperature range, ΔT constant

Dependence of whisker length on dwell time

The effect of the dwell time on the whisker growth at constant cycle numbers and ΔT is plotted in Figure 7.

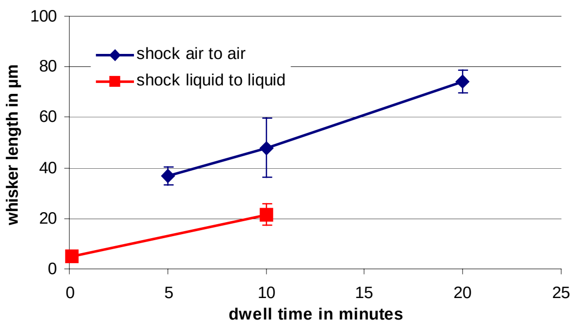

Figure 7 - Whisker growth vs. dwell time at various cycle types (ramp rates and atmosphere), 500 cycles, constant T-range –40 °C / +85 °C

Obviously the maximum whisker length increases with the dwell time for dwell times between 0.16 min and 20 min. This trend in dwell time is not expected to remain linear because the driving force for whisker growth should go to zero after complete relief of the compressive stress in the tin plating – either by whisker growth or annealing. Thus very long dwell times will not cause unlimited whisker growth. In fact, tin plated on FeNi42 does not form whiskers during constant temperature aging tests at 50 °C to 60 °C up to one year. However, the effect of dwell time needs to be studied over a wider range of dwell times and temperature ranges to clarify the relationship between whisker growth and dwell time.

The fact that liquid to liquid cycling results in smaller whiskers than air to air shock cycling may be explained in one of two ways. First, some of the whiskers may simply have broken due to the impact of the liquid when transferring the components rapidly from one to the other liquid. Second, oxidation may contribute to stress generation in the tin layer by constraining the tin plating This would mean that cycling in air would have an additional stress source, which is suppressed in the inert media used for the liquid to liquid cycling.

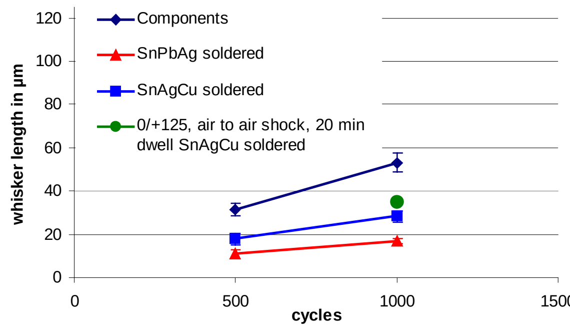

Figure 8 – Whisker growth after –40 °C / +85 °C, 5 K/min, 30 min dwell on unsoldered components and modules SnAgCu,- or SnPbAg soldered.

Dependence of whisker length on soldering

In Figure 8, the whisker behaviour of as-manufactured components is compared to the whisker behaviour of components that have been soldered using a SnPbAg or SnAgCu surface mount assembly process. It is clear that longer whiskers are formed on components that have not experienced a surface mount assembly process. Although surface mount assembly reduced the propensity of the tin plating to form whiskers, whiskers did form in regions of the plating that were not covered by solder (the upper portion of the leads).

The soldered components show significantly smaller whisker than the non-soldered components under the same cycle conditions (Figure 8). The longest whisker on SnAgCu soldered components is of approximately half the length of that on the non-soldered control group. SnPb-soldering reduces the maximum length to almost one third. Although soldering with SnPbAg and SnAgCu had a significant effect on whisker growth, a surface inspection of the soldered components on regions of the plating that were not wet by solder did not reveal any fusing or recristallisation. Possibly there are mechanisms, which act to reduce whisker growth aside from obvious recristallisation or fusing. To detect such an influence on the microstructure would require a more sophisticated investigation, such as x-ray diffraction or transmission electron microscopy. Another much simpler explanation for the smaller whiskers measured after surface mount assembly is based on the randomly distributed whiskers and the sporadic growth of long whiskers. An essential fraction of the leads is covered by solder and reflowed. Thus the area for undisturbed whisker growth is significantly smaller for the assembled components. No whiskers can be found in the solder wetted area. The wetting of SnPbAg is usually somewhat better, which would reduce the exposed electroplating relative to the parts soldered with SnAgCu.

Dependence of whisker length on Sn vs. SnPb plating
Summarising the results on the SnPb plated control group, it can be stated that whiskers have grown on the SnPb plating in all thermal cycle conditions that grew whiskers on tin plated components. After 1000 cycles the SnPb plating on alloy 42 is densely covered with whiskers. However, the longest whiskers on SnPb plated FeNi42 were measured as approximately 20 µm, even in the worst conditions identified for tin on FeNi42.

Attempt to create a predictive model
The main goal of thermal cycle testing is to evaluate whether whisker failures could occur in product applications, ranging from computers to telecommunications equipment. Typically, electronic products undergo temperature cycling due to environmental exposures (night vs. day or indoors vs. outdoors) and operational exposures (on vs. off). These thermal cycles will not typically have the same temperature range, ramp rates, or dwell times that have been applied during testing. It is desirable to have a mathematical prediction for a field condition based on the available test results.

Based on the available data, there appears to be a linear relationship between the maximum whisker length, W, and the thermal cycle range, ΔT, for a given number of thermal cycles, as shown in Figure 5. For 500 cycles, this relationship is:

$$W \approx a_1 \Delta T - a_2$$

where a_1 = 0.16 and a_2 = 17. However, this relationship between W and ΔT will change, depending on the number of thermal cycles applied. In effect, the empirically derived values for a_1 and a_2 depend on the number of cycles applied, C.

$$W \approx (a'_1 \Delta T - a'_2) C^{a_3}$$

This relationship between maximum whisker length, W, and the number of thermal cycles, C, is parabolic: For instance, when ΔT = 100 °C, a'_1=0.027, a'_2=0.74 and a_3 = 0.5. However, this parabolic relationship of a_3 = 0.5 breaks down and gives a non-conservative prediction for whisker length at low ΔT, especially at high numbers of thermal cycles. Unfortunately, low ΔT and high numbers of thermal cycles are close to the electronic product service conditions that we would like to predict. It appears that the empirically derived value for a_3 depends on the thermal cycle range ΔT.

$$a_3 = -0.0062 \Delta T + 1.09$$

A better prediction for the dependence on cycles may include a dependence of a_3 on ΔT. This relationship can be more easily observed by plotting ln$W$ vs. ln$C$, as previously done for whiskers observed in Sn plating on a Ni plated ceramic passive component[9].

This means that as the thermal cycle range, ΔT, decreases, the relationship between the whisker length and the number of cycles becomes linear. This fits the current data set, however, it does not seem reasonable to assume that a linear relationship between W and C would continue infinitely.

It is possible that the rate of whisker growth depends on the whisker length not simply the number of cycles or that whisker growth depends on the damage to the plating as mentioned earlier in the discussion. A dependence of whisker growth rate on the length of the whisker might explain the more significant decay in growth rate within 2500 cycles for the larger ΔT condition. This decay may also be explained by the damage observed in the tin plating after 2000 thermal cycles at ΔT= 100 or 125°C. Based on the data collected thus far, a decay in growth rate for the ΔT = 40 °C test condition has not been observed.

Eventually a predictive model would need to include the effect of dwell time on whisker length (Figure 7). However, the current data set was created over a small range of dwell time 0.16 – 20 min. Over this range, the dependence on dwell time was linear, but this linearity is not expected to continue infinitely. Thus the linear relationship over the range from 0.16 min to 20 min dwell time should not be extrapolated to thermal cycles in service conditions that may cycle once a day.

In addition, the effect of soldering appears to be significant, however, a mathematical relationship cannot reliably be developed between as-manufactured and assembled components. The reason for the decrease in whisker growth rate is not fully understood. As explained with Figure 8, decreased maximum whisker length after soldering may be statistical or physical.

Conclusion
Tin plated FeNi42-based components have been investigated in various conditions of temperature cycling. The whisker length was measured in intervals (250-2500 cycles), so that the dependence of whisker growth rate on various parameters could be investigated. These parameters included temperature

range (ΔT), upper and lower temperature limit of the cycling, dwell time, and ramp rate. The conclusions from this work are as follows:

- Whisker growth in tin plated on alloy 42 has a strong dependence on the applied thermal cycles. Generally thermal cycling has a strong effect on tin plated alloy 42, but a negligible effect on tin plated copper. This discrepancy in the impact of thermal cycling on tin plated copper and tin plated alloy 42 may be explained by the difference in CTE mismatch in the two cases, which is expected to generate higher compressive stresses in tin plated alloy 42 in thermal cycling. This compressive stress is believed to be a driving force for whisker growth.

- Whiskers length may have a parabolic relationship to the number of thermal cycles.

- Temperatures below -15 °C do not appear to influence the whisker growth at moderate dwell times (e.g. 10 min). Although they may affect the timing for a decay in whisker growth.

- The relationship between whisker length and ΔT is fairly linear with whisker length increasing monotonically with ΔT.

- Component assembly on printed circuit board by SnAgCu soldering reduces the maximum whisker to half the length, SnPbAg soldering reduces the maximum length to one third.

- SnPb plating on FeNi42 grows whiskers in the same temperature cycling conditions as tin plated FeN42 does. The whisker density is comparable, but the maximum length is significantly smaller.

Future work

More testing is needed to obtain a predictive model for whisker growth in electronic products. In particular, the effect of dwell times above 20 min are needed and the low ΔT testing should be extended to longer times to determine whether a parabolic relationship is appropriate or whether an upper limit for whisker length.

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References

[1] Zhang, Yun; Schetty, Rob; "Whisker Growth: The Substrate Effect and Beyond" Proc. IPC / JEDEC 2nd International Conference on Lead-free Electronics and Assemblies, Taipeh, Taiwan, Dec. 2002

[2] Xu, C. at al. "Whisker Prevention" Proc. APEX 2003, S-18-3-1, California USA

[3] Egli, A. et al. "Where Crystal Planes Meet: Contribution to the Understanding of the Tin Whisker Growth Process" IPC Annual Conference Nov. 2002, New Orleans, S-08-03-01

[4] Choi, W.J. et al "Structure and Kinetics of Sn Whisker Growth on Pb-free Solder Finish, Proc. 52nd Electronic Components & Technology Conference (ECTC) 2002, pp. 628-633

[5] Kadesch, J. S. "Effects of Conformal Coat on Tin Whisker Growth" Proc 37th IMAPS Nordic Annual Conference, September 2000, pp. 108 - 116

[6] Dittes, M; Oberndorff, P; Petit, L; "Tin Whisker Formation – Results, Test Methods and Countermeasures" Proc. 53. Electronic Components & Technology Conference (ECTC), New Orleans, 2003, pp. 822 – 826

[7] Oberndorff, P; Dittes, M; Petit, L; Chen, C.C; Kluizenaar, E.E. de "Tin Whiskers on Lead-free Platings" Proc. SEMI Technology Symposium, Advanced Packaging Technologies II, August 2003, Singapore, pp 51-55

[8] Oberndorff, P; Dittes, M; Petit, L; " Intermetallic Formation in Relation to Tin Whiskers" Proc. IPC/Soldertec International Conference on Lead-free Electronics – Towards Implementation of the RHS Directive, June 11-12, 2003, Brussels, Belgium, pp 170-178

[9] Ando, T.; Shibata, M.; Okada, S.; Namasuya, Y. "Stress analysis and accelerated evaluation of tin whisker under thermal shock stress"