

# Whisker Testing: Reality or Fiction?

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## Abstract

With the introduction of matte Sn as a Lead free finish for semiconductor leadfinish the need for a whisker standard test increases. Around the world several consortia are proposing different standard tests, like JEITA in Japan, NEMI in the US and the E3 (= cooperation of Infineon, STMicroelectronics and Philips) in Europe.

The E3 joined forces in a EU funded project, PROTIN, to solve the mystery of the whisker growth mechanism and to propose an industry wide whisker test.

For this purpose, the E3 have built up an enormous database of whisker growth in various conditions. In this paper we give an update on the previously reported and ongoing experiments to discover the main factors influencing whisker growth. We found different causes for whisker growth based on the choice of substrate material. Also other influencing factors such as temperature, humidity and oxidation level will be discussed. Based on the different test results, theories for whisker growth mechanisms are presented. Countermeasures to whisker growth are proposed based on these theories.

It is our opinion that the proposed whisker tests, mentioned earlier, should be based on the actual whisker growth mechanisms. Besides this, the tests should represent actual conditions that the components will be exposed to during field life. Therefore, the proposed standard tests will be evaluated for these criteria.

## Introduction

With the upcoming lead free legislation many component suppliers are switching from electroplated SnPb to electroplated matte Sn as finish for the leads of their components. Although Sn platings have historically been associated with whiskers an industry wide whisker test has never been proposed.

This in combination with uncertainty about the mechanism of whisker growth results in qualification problems for both semiconductor supplier as well as EMS and OEMs. Adding to this problem is the fact that whisker growth can take place already during storage as well as during field conditions.

It is the authors opinion that an industry wide whisker test should be based on actual whisker growth mechanisms, in order to prevent false rejects, while at the same time assuring that platings with high propensity of whisker growth will be rejected. Therefore, we will discuss several factors leading to whisker growth. This based on over three years of study within all three companies.

## Experimental

Tin layers have been deposited on typical lead-frame materials, such as C19400 (CuFe2P), C18070 (CuCrSiTi), C70250 (CuNi3Si1Mg), C14415

(CuSn0.15), Alloy 42 (FeNi42), copper plated Alloy 42 and others. Various electrolytes from six different suppliers have been used, while both continuously operating electroplating production lines and laboratory scale set-ups were employed. The thickness of the deposits was varied between 1.5 µm to 15 µm.

Plating surfaces have been studied with both optical microscopy and scanning electron microscopy (SEM). In order to influence the whisker growth, several heat treatments and storage conditions have been used. The storage conditions have been selected based on the publications of various companies and institutes.

Cross-sections of the plating layers have been prepared and viewed with optical microscopy and SEM. To study the intermetallic compounds formed after plating and storage, a commercially available Sn stripper was used that selectively etches the Sn, while not attacking the intermetallic compound and lead frame material.

## Results and Discussion

Nowadays it is generally agreed upon that whiskers grow because of compressive stress within the plating layer. This stress can be caused by a multitude of factors, which makes the whisker growth mechanism such a difficult subject. In the text below we will discuss several of the

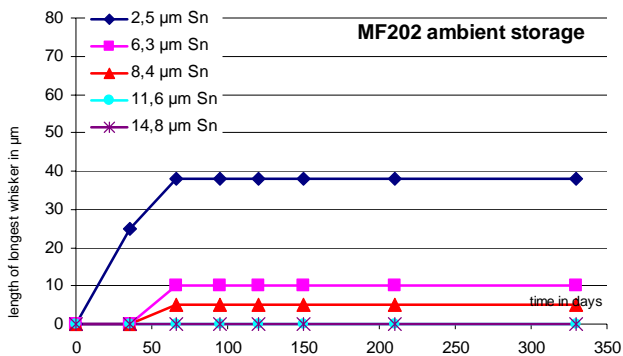
causes we identified in our research, which include the main causes for compressive stress leading to whisker growth, and relate these causes to test conditions.

**Plating Type and Process Parameters**

First of all, the difference between matte Sn and bright Sn should be stressed here. The main difference between these two is that the bright Sn has more organic compounds incorporated in the deposit in order to give it a shiny appearance. These organic co-deposits often incorporate a compressive stress, which in turn leads to whisker growth.<sup>1</sup> Therefore, bright Sn usually has a higher propensity than matte Sn, which is proposed by most of the component suppliers. It should also be remarked that the few failures by whisker growth that are described in open literature are caused by bright Sn deposits. The remainder of this publication will deal with matte Sn, unless explicitly stated.

The process parameters for the plating bath are described by the plating bath supplier and it is advisable to stay within process window proposed by this supplier. During our research we e.g. found that if the current density was set outside the process window it lead to an irregular plating surface.

As is shown in Fig. 1, the thickness of the plating layer has a large influence on the whisker propensity.



**Fig. 1: Maximum whisker length as a function of time with different plating thickness under ambient storage on a Cu based leadframe**

We explain this difference by the fact that a thin layer cannot absorb that much stress and therefore, will have a higher whisker propensity.

**Leadframe Material**

Already early on in our research we discovered that the leadframe material has an enormous influence on whisker growth. Generally we can differentiate here between two types of leadframe materials;

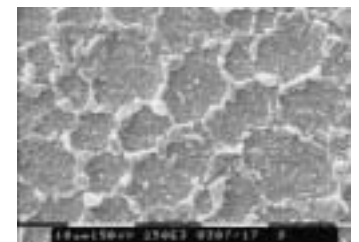
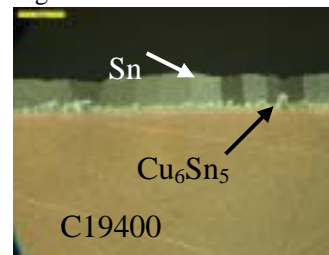
- 1) Cu-based with a coefficient of thermal expansion (CTE) around 17 ppm/° and
- 2) NiFe with a CTE around 5 ppm/°

both having a different whisker growth mechanism. This is caused by effects as discussed below.

ad 1) Composition (intermetallics)

The effect of the composition in relation to intermetallics is in increasing whisker propensity refers to Cu based leadframes. In these cases whiskers will grow during the time period that the components are stored at more or less isothermal conditions.

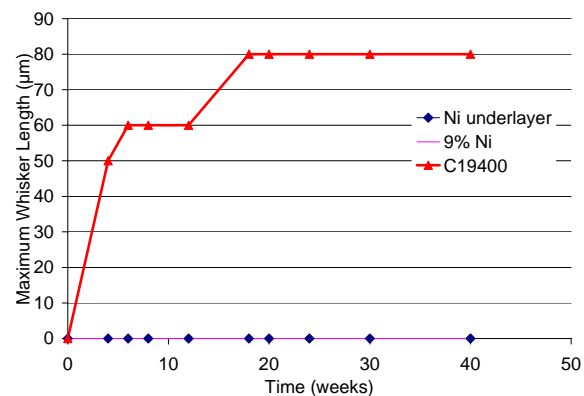
During storage Cu<sub>6</sub>Sn<sub>5</sub> intermetallic will grow at the interface of the Cu leadframe and the Sn plating. Due to the low temperatures the prevalent mechanism of growth will be through grain boundary diffusion. Due to the columnar structure in matte Sn this will result in irregular intermetallics in the grain boundaries of Sn as shown in Fig. 2.



**Fig. 2a: Cross-section of a C19400 substrate plated with ~12 μm Sn showing the individual grains of Sn. The marker depicts 15 μm.**

**Fig. 2b: Top view of the Cu<sub>6</sub>Sn<sub>5</sub> intermetallic after 6 months ambient storage and subsequent selective etching of Sn**

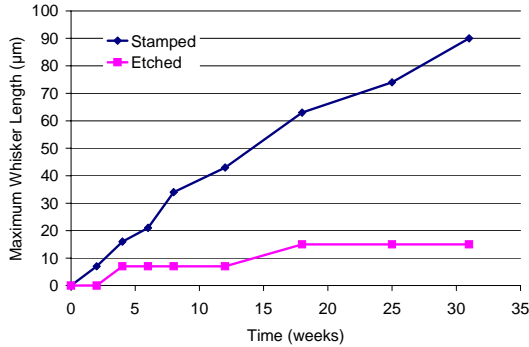
The formation of Cu<sub>6</sub>Sn<sub>5</sub> in the Sn grain boundaries results in compressive stress in the Sn layer, as can be shown by comparison of the molar volumes of the different constituents.<sup>2</sup> According to the authors this is the main cause for compressive stress in matte Sn platings on Cu based leadframes. This theory is also supported by data shown in fig. 3.



**Fig. 3: Maximum whisker length as a function of time comparing two different Cu based leadframes (C19400 and Cu-based with 9% Ni) and a Cu leadframe with a Ni underplating under ambient storage (results for coupons with ~ 7.5 μm Sn plating)**

If a Ni underlayer is used, the resulting intermetallic after storage will not be  $\text{Cu}_6\text{Sn}_5$  but  $\text{Ni}_3\text{Sn}_4$ , which due to its different structure will impose less compressive stress or even a tensile stress.<sup>2</sup>

In the case of the leadframes with additional Ni a ternary intermetallic will form with different properties.<sup>3</sup> Besides the above described effect we also found an effect of the pretreatment of the leadframe. As can be seen in Fig. 4, the whisker propensity of an etched leadframe compared to that of a stamped leadframe of the same composition is considerably less.



**Fig. 4: Maximum whisker length as a function of time comparing an etch leadframe with a stamped leadframe of the same composition (plating thickness ~7.5 µm)**

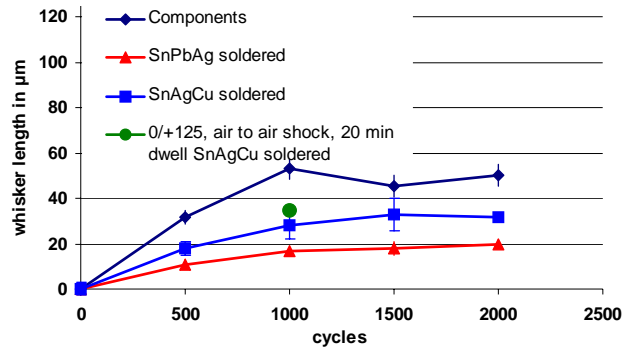
ad 2) CTE mismatch

The difference in intermetallics also explains why no whisker growth has been observed on a FeNi42 leadframe at isothermal storage. Like with a Ni underlayer the prevalent intermetallic growing in this case is  $\text{Ni}_3\text{Sn}_4$ .

However, if a FeNi42 (Alloy 42) leadframe plated with Sn is submitted to temperature cycling, whiskers will grow. Noting that temperature cycling on Cu-based leadframes did not result in excessive whisker growth, it has been concluded that this difference in whisker performance is due to the difference between coefficient of thermal expansion (CTE) of Alloy 42 and Sn (CTE(Alloy 42) = 5.5 ppm/K; CTE(Sn) = 23 ppm/K), which is much smaller between a Cu-alloy leadframe (CTE(Cu) = 17 ppm/K) and Sn. In this case the mismatch of the CTE's produces the compressive stress needed for whisker growth. A study performed to identify the main influencing parameters for temperature cycling was reported recently.<sup>4</sup>

However, components will only be submitted to temperature cycling after assembly. As can be seen in Fig. 5, whisker growth after assembly and subsequent temperature cycling resulted in smaller whiskers than on bare components.

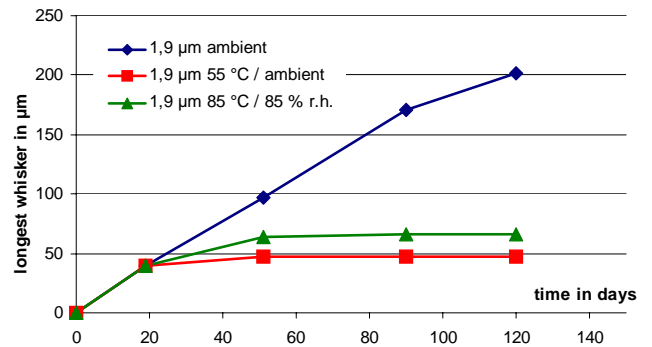
In the case of Cu leadframes temperature cycling on bare components results in small whiskers (up to approximately 30 µm), but temperature cycling on assembled components results in no or very small (<10 µm) whiskers.



**Fig. 5: Whisker growth after temperature cycling (-40 °C/85 °C, 5K/min, 30 minutes dwell time) comparing bare components and modules (soldered with SnAgCu and SnPbAg)**

### Temperature

As is shown in the figure below whisker growth is greatly reduced with increased temperature. This can be explained by the findings of the earlier paragraph for Cu based leadframes. Instead of irregular intermetallic formation through grain boundary diffusion, the diffusion mechanism will slowly shift with increasing temperature to bulk diffusion. This will result in a more regular intermetallic layer.



**Fig. 6: Maximum whisker length as a function of time at different temperatures on a Cu based leadframe**

Apart from this, with increasing temperature whisker growth as stress relief will have a more severe competition of annealing, where it has to be kept in mind that due to the low melting point of Sn (232 °C) annealing will occur at very low temperatures.

While whisker growth is slowing down with increased temperatures, lower temperatures than ambient also do not lead to extensive whisker growth.<sup>5</sup> Again this can be

explained by diffusion. At temperatures well below ambient the intermetallic formation will be very slow, resulting in only limited intermetallic. Besides this, also the diffusion speed of the Sn itself, necessary for the actual whisker growth is very low.

The discussion of temperature leads us to temperature treatments of the plating layer which can be done before assembly or are a regular effect of the assembly operation, e.g. reflow.

### Postbake

Within the E3 a heat treatment step of 1 hour at 150 °C is applied for Cu leadframes directly after plating in order to mitigate whisker growth as explained in previous publications.<sup>2,5-7</sup>

Due to the bulk diffusion at this increased temperature a much more regular intermetallic layer, consisting of  $Cu_3Sn$  and  $Cu_6Sn_5$  will form resulting in less compressive stress. Apart from that the grain boundaries of the Sn will shift, resulting in larger grains and less grain boundaries. Furthermore, the more regular intermetallic layer will result in a diffusion barrier for further growth of the  $Cu_6Sn_5$  intermetallic, inhibiting further irregular growth by grain boundary diffusion at ambient conditions.

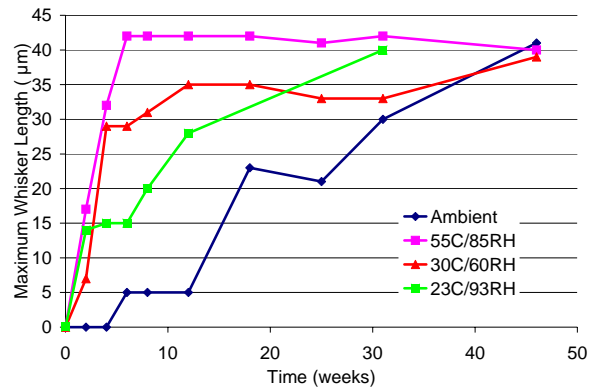
### Reflow/Assembly

During field life the components will be attached on a printed circuit board, often through a reflow operation. This soldering step ensures that the plating on the leadframes will in some cases reflow/melt or at least see a high temperature for some time. Due to this step the whisker propensity is actually decreased and not only for NiFe based leadframes as explained above, but also for Cu based leadframes.

The explanation for this fact is that after reflow all the present stress within the Sn plating is released. Besides this, during the reflow operation a regular intermetallic layer on Cu based leadframes will be formed that will serve as a diffusion barrier for further intermetallic growth at a later time, similar to the layer produced during postbake. Also recrystallization and grain growth will occur during the reflow operation.

### Humidity and Oxidation

As can be seen in Fig. 7 it is shown that humidity can accelerate whisker growth. One of the possible explanations can be that oxidation products form on the Sn surface. These oxidation products are able to penetrate the grain boundaries from the top down and thus introducing additional compressive stress. However, the additional volume of the oxidation products would be less than the additional volume created by intermetallics. Therefore, the caused compressive stress would be less than is the case for irregular intermetallic formation.



**Fig. 7: Whisker Growth under different conditions on a C7025 leadframe (thickness ~ 7.5 µm)**

At the same time an oxidation layer can inhibit whisker growth as argued by K.N. Tu, since the whisker has to grow through this oxide layer.<sup>8</sup> Here it is important to realize that two different Sn oxides exist: SnO and SnO<sub>2</sub>. At the moment we are looking into the properties of these different oxides to evaluate the influence on whisker propensity of each and to distinguish the optimized growth conditions of the oxide layers.

However, for these test conditions with high humidity often no correlation can be found to actual field conditions. The often used test condition of 60 °C/93 % r.h. can even lead to condensation on the leadframes and false rejects.<sup>9</sup>

### Mechanical Induced Stress

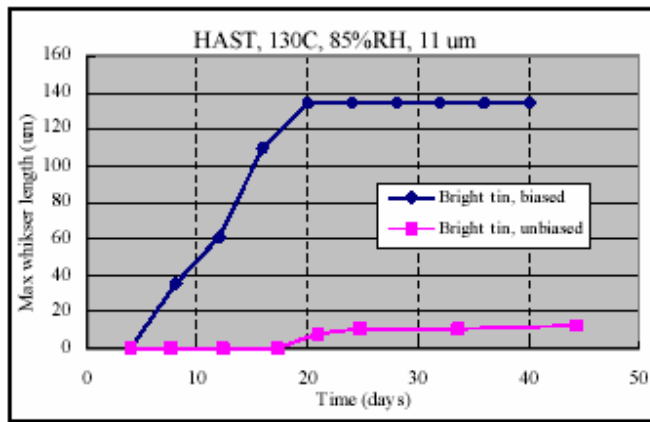
Mechanically induced stress was reported to influence whisker growth if applied continuously.<sup>10</sup> Unfortunately, using mechanically induced stress as a whisker test encounters two major problems;

- there is no actual relation with field conditions for soldered components;
- it is reported not to be discriminative between high and low whisker propensity.

Although continuously mechanically induced stress reportedly induces whisker growth we did not find a significant influence of the trim/form action on whisker formation in our research. Actually, whisker propensity on components in leadstrips was found to be higher than on trim formed components.

### Bias

In some studies bias is identified to accelerated whisker growth. During our study we were not able to confirm this for matte Sn finishes, neither for ambient conditions nor for 60°C/93 % r.h.<sup>11</sup> On bright Sn, however, we did find a significant acceleration effect as shown in fig. 8. It is our hypothesis that this has to do again with the organic deposits in the bright Sn as discussed earlier.



**Fig. 8: Maximum whisker length as a function of time on Bright Sn for bias and unbiased conditions (130 °C/85 % r.h.)**

### Orientation

Although orientation can have an effect on whisker propensity as stated in several publications, there are practical limitations for using this parameter for qualification purposes.<sup>12,13</sup>

### Conclusions and Test Method Proposal

It is shown that whisker formation is a multifaceted problem. Nevertheless, it is possible to identify the major causes for whisker growth on matte Sn.

In order to do so it is important to distinguish between leadframe materials;

- for Cu based leadframes irregular intermetallic growth ( $\text{Cu}_6\text{Sn}_5$ ) is the major cause
- while for leadframe materials or underlayers with a large CTE mismatch compared to the Sn finish (CTE ~ 23 ppm/K) this mismatch is the major cause for whisker growth.

According to the authors whisker tests should be related to field conditions. Therefore, a distinction between storage life of a component and actual field life should be made. In the first case, isothermal storage can be applied as a test condition, possibly with higher humidity in order to get an accelerated effect. In the latter case components should be tested in assembled state and a temperature cycle test can be applied. However, from experience it is known that on leadframes matching Sn considering their CTE these tests will not result in critical whisker growth.

Therefore we propose two different test, which shall be applied with respect to the material composition.<sup>14</sup> The first test is isothermal storage in air at 30 °C and a relative humidity of 60 % for 8 weeks of a 3 µm plating layer. It shall be applied to any tin based finish type and on any base material. This test actually represents storage conditions, while a thin layer is used to show the propensity for whisker growth in a short period as

explained in the sections above. In order to qualify we propose a critical whisker length of maximally 20 µm.

The second test is a temperature shock test from -40/85 °C for 500 cycles for components with a leadframe or underlayer with a CTE < 15 ppm/K. Since this test is intended to indicate whisker propensity during service life, the components are to be soldered on a printed circuit board before testing. In this case we propose an acceptance criterion of 50 µm critical length.

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### References

- 1) Xu, Chen et al, "Understanding Whisker Phenomenon Part II: Competitive Mechanisms", Proc. SurFin '01, Nashville, TE, June 2001
- 2) P. Oberndorff, M. Dittes, P. Crema, "Whisker Formation on Sn Plating" Proc. IPC / JEDEC 5th Intern. Conference on Lead free Electronic Assemblies and Components, March 2004, San José, USA
- 3) P. Oberndorff, "Lead free Solder Systems: Phase Relations and Microstructures", Ph.D. thesis, Eindhoven University of Technology, June 2001, Eindhoven, The Netherlands
- 4) M. Dittes, P. Oberndorff, P. Crema, V. Schroeder, "Tin Whisker Formation in Thermal Cycling Conditions", Proc. Electronics Packaging Technology Conference (EPTC) December 2003, Singapore pp 183-188
- 5) M. Dittes, P. Oberndorff, L. Petit, "Tin Whisker Formation – Results, Test Methods and Countermeasures", Proc. 53. ECTC 2003, New Orleans, p. 822-826
- 6) P. Oberndorff, M. Dittes, L. Petit, "Intermetallic Formation in Relation to Tin Whiskers", Proc. IPC/Soldertec International Conference on Lead free Electronics – Towards Implementation of the RHS Directive, June 2003, Brussels, Belgium, p. 170-178
- 7) P. Oberndorff, M. Dittes, L. Petit, C.C. Chen, J. Klerk, E.E. de Kluizenaar, "Tin Whiskers on Lead free Platings" Proc. SEMI Technology Symposium, Advanced Packaging Technologies II, August 2003, Singapore, p. 51-55
- 8) K.N. Tu, Interdiffusion and Reaction in Bimetallic Cu-Sn Thin Films, Acta Met. 21 (1973) p. 347
- 9) Private communication with John Osenbach, Agere Systems, February 2004
- 10) R.M. Fisher, L.S. Darken and K.G. Carroll, Accelerating Growth of Tin Whiskers, Acta Met. 2 (1954)p. 368
- 11) P. Oberndorff, C.C. Chen, E. Yu, J. van de Water, "Whisker Mitigation by Postbake: Test Results", Proc. IPC/Soldertec Global 2<sup>nd</sup> International Conference on

Lead free Electronics, June 2004, Amsterdam, The Netherlands

12) K. Whitlaw, A. Egli, M. Toben, “ Preventing Whiskers in Electrodeposited Tin for Semiconductor Lead Frame Applications”, Proc. IPC/Soldertec International Conference on Lead free Electronics – Towards Implementation of the RHS Directive, June 2003, Brussels, Belgium

13) R. Schetty, “Electrodeposited Tin Properties and Their Effect on Component Finish Reliability”, Proc. IPC / JEDEC 5th Intern. Conference on Lead free Electronic Assemblies and Components, March 2004, San José, USA

14) M. Dittes, P. Oberndorff, P. Crema, “Whisker Root Cause and Respective Test Conditions, NEMI Tin Workshop, ECTC June 2004. Las Vegas USA (to be published in IEEE CPMT)