SAND2011-9133 C

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Recent Tin Whisker Research at Sandia

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Abstract

Tin (Sn) whiskers are conductive Sn filaments that grow from Sn-plated surfaces, such as surface finishes on electronic packages. The phenomenon of Sn whiskering has become a major concern in recent years due to requirements for lead (Pb)-free soldering and surface finishes in commercial electronics. Pure Sn finishes are more prone to whisker growth than their Sn-Pb counterparts and high profile failures due to whisker formation (causing short circuits) in space applications have been documented.[1] Despite the long history of Sn whisker research and the recently renewed interest in this topic, a comprehensive understanding of whisker growth remains elusive. This overview will describe recent research at Sandia National Laboratories to characterize Sn whisker growth with the aim of understanding the underlying whisker growth mechanism(s). Topics to be covered include Sn plating of samples for whisker growth studies, characterization by electron microscopy and other techniques, and experiments to study whisker growth on microelectronic parts. The overview is intended for those in the structural brazing and soldering community, who may not be familiar with tin whiskers encountered in microelectronics.

* Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Introduction

Tin whisker research usually involves electroplating of Sn or a Sn alloy on a copper alloy or alloy 42 (Fe based) substrate. The electroplated Sn finish simulates those used on component leads for Pb-free microelectronics. Researchers often measure the stress in the deposit immediately after plating and as a function of time thereafter. The stress can be measured by curvature techniques with thin substrates [2] or by X-ray analysis methods. The buildup of compressive stress within the Sn film is generally accepted as the driving force for whisker formation. It is also believed that the growth of Cu_6Sn_5 intermetallic compound (IMC) at the film/substrate interface can maintain the stress over long periods of time, although the IMC is not strictly necessary for whisker growth.[3] Although there are several theories in the literature, a full explanation of the whisker growth phenomenon remains elusive. The following overview discusses some of the research projects being carried out at Sandia National Laboratories to further understand the underlying mechanism(s) of tin whisker growth.

Discussion of Tin Whisker Research at Sandia

Dynamic Recrystallization (DRX) Model

A recent project at Sandia involved the search for a metallurgical process to describe whisker growth. The phenomenon of dynamic recrystallization (DRX) was proposed to describe the whisker growth process.[4,5] In this description, the whisker growth phenomenon is a combination of two processes: (a) dynamic recrystallization (DRX) that is responsible for the explicit growth of the whisker filament and (b) long-range, anomalously fast, solid-state diffusion that provides the source of Sn atoms that creates the whisker. Initial experiments determined a parameter space of strain rate, grain size, and strain required to initiate DRX in Sn coatings.[4,5] More recently, these parameters were used to assess whisker growth from an evaporated 1.0 micron thick Sn film. The stress conditions were 6.0 MPa and 8.0 MPa at a test temperature of 100˚C. These parameters produced hillocks rather than long filamentary whiskers. Hillocks are commonly observed when the defect growth is not localized to a single grain, but rather incorporates several surrounding grains which may continue to grow laterally over time.[2] Figure 1 shows SEM photomicrographs of Sn hillocks formed under the experimental conditions described above. Although the results confirmed the parameters necessary for DRX to occur, the process was not localized to a single Sn grain and, thus, lateral hillock growth occurred. From the results of this study and many others in the literature, the question remains as to why the mass buildup is localized to form a long filamentary whisker in some situations and not in others. Compared to hillock growth, the formation of long thin whiskers is of much more concern for electrical shorting or foreign object debris (FOD) in microelectronics applications.

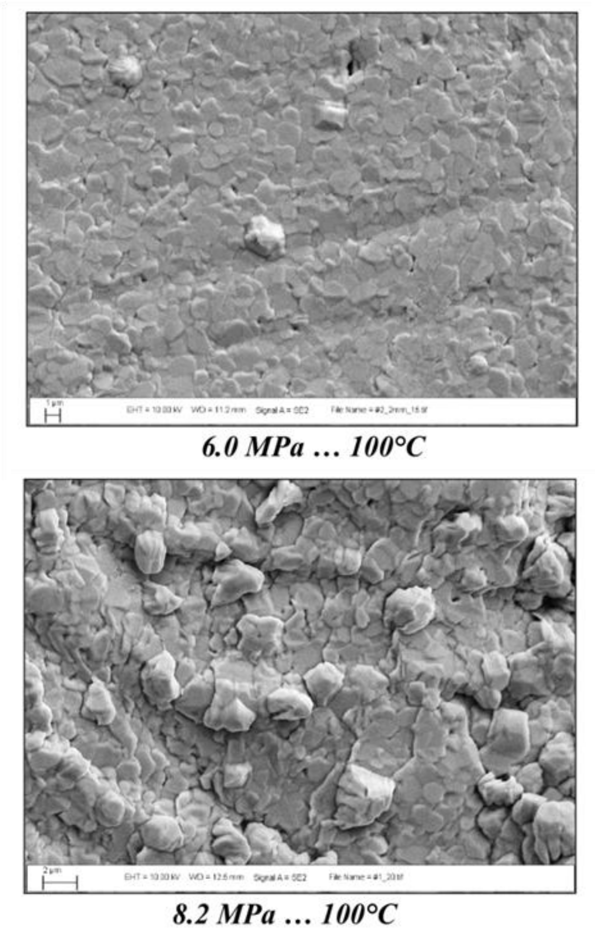


Figure 1. SEM photomicrographs showing hillock growth on 1.0 µm Sn films exposed to strains and strain rates determined by the two compressive stress conditions of 6.0 MPa and 8.2 MPa at 100°C.

Sn Whisker Characterization

Building on these ideas, another project at Sandia has focused on the following questions: (a) Why do whiskers form only in certain locations within a Sn film? (b) Why do some circumstances produce long filamentary whiskers as opposed to short wide hillocks? The answers most likely lie within the details of the local microstructure of the coatings. In this work, extensive characterization was performed on Sn whiskers including scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and focused ion beam (FIB) cross sectioning. The goals of the project were to understand whisker morphology and crystallography. This “local scale” information could shed light on the tendency for whiskers to grow only in certain locations and the factors that confine the growth to a thin filamentary structure in some cases and broader, less risky hillocks in other instances.

The first step was to produce Sn films that grew whiskers. Table 1 shows electroplating parameters that successfully produce whisker-bearing samples. The Sn films were approximately 1-2 microns thick deposited on pure Cu sheet substrates. No external stresses were applied to the samples after plating. It should be noted that many plating parameters were explored that resulted in Sn films that did *not* produce whiskers. Thus, the intrinsic plating stress appears to be important. An alkaline plating bath, with a rotating disk electrode, was used because it was found to produce “good” samples with many whiskers. This type of plating was not meant to reproduce Sn finishes commonly used in industry, which often employ an acidic plating electrolyte such as a methane-sulfonate bath.[2,3]

Table 1. Plating parameters used with an alkaline stannate (sodium or potassium stannate) plating bath.

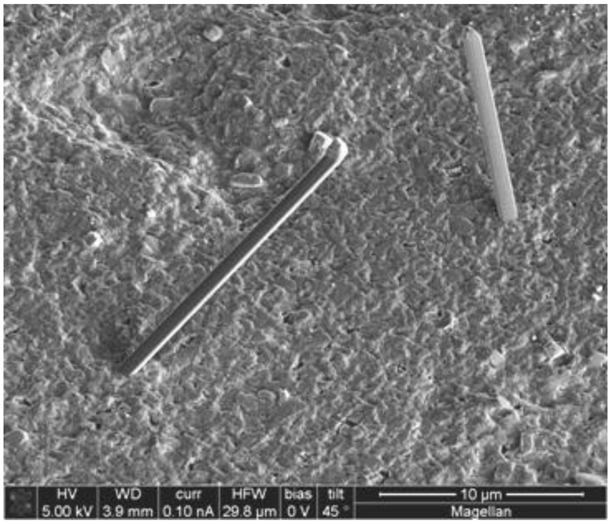
Plating mode	E (mV) or I (mA)	Time (min)	Temp. (˚C)	Agitation (rpm)	Approx. Thickness (um)	Whiskers ?
CP	-2.47mA	40	70	1000	2.4	YES
CA	-1500mV	30	70	1000	1.8	Some
CP	-20.0mA	5	70	1000	2.2	Few
CP	-20.0mA	10	70	1000	4.4	few
CP	-20.0mA	10	70	1000	1.5	YES
CA	-2400mV	15	70	1000	1.5	yes
CA	-1900mA	10	70	1000	0.68	YES

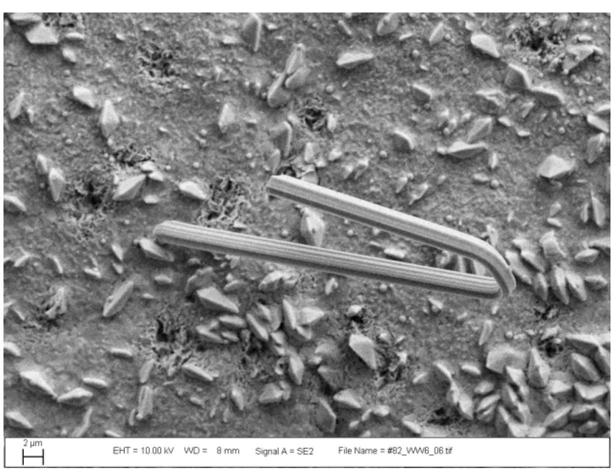
CP = chrono potentiometry (constant current)
CA= chrono amperometry (constant voltage)

Once the samples were produced, the whiskers were characterized by SEM. Figure 2 displays a few of the many types of whiskers observed in this work. Whisker diameters are commensurate with the grain size in the film, i.e. about 1 micron. Whiskers grow from their base, not at their tip. The various whisker types observed included straight and kinked whiskers, curved whiskers, hillocks, and combinations of whiskers/hillocks, etc. Many of these whisker types have been observed by other researchers [6] and they emphasize the concept that different mechanistic details are responsible for the various types of whisker shapes and other associated growth structures.

Whisker growth kinetics were also measured as part of this research.[7] If whisker lengths or growth angles are to be measured accurately, it is important that the whiskers be viewed at more than one SEM tilt angle.[7,8] One important finding from this work is related to the kink process. It was found that whiskers often slow down or stop growing when they change direction.[7] Thus, it is surmised that the kink/bend process also removes the local (crystallographic, diffusion, or other) conditions necessary for long-term whisker growth.

Tin whiskers were also characterized using electron backscatter diffraction (EBSD). This is a method whereby crystallography can be determined within the SEM. EBSD has shown that long thin whiskers are single crystals.[7] This is true even for kinked whiskers. Several EBSD methods have been utilized to determine the crystallographic growth directions of tin whiskers.[9] The analysis of many whiskers within Sandia studies has determined that the low index directions, i.e. <001>, <100>, <101>, and <111>, are the major crystallographic growth directions. This finding may be useful for atomistic modeling of the whisker growth process.





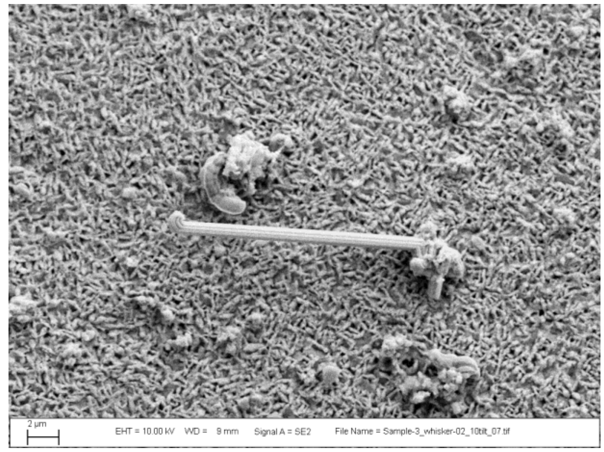


Figure 2. SEM examples of straight, kinked, and curved whiskers, and a whisker that subsequently grew as a hillock or "odd-shaped eruption".

Another useful technique for characterizing Sn whiskers is focused ion beam (FIB) cross-sectioning. Figure 3 exhibits FIB cross-sectional images of a Sn whisker. A serial sectioning technique was used to show the complex morphology of the whisker and its surrounding grains. In particular, note the very complex morphology of the Cu_6Sn_5 layer. The whisker also displays a chevron or "V" shaped grain boundaries at its base. This morphology has been shown by several other researchers.[10] The FIB serial sectioning technique has recently been combined with in-situ EBSD and energy dispersive spectroscopy (EDS) to give a complete three-dimensional representation of the morphology, crystallography, and microchemistry of Sn whiskers. Such methods are proving to be useful, not only to determine the characteristics of the whisker grain itself, but also to determine such properties of the grains surrounding the whisker. Full characterization of these grains and grain boundaries may be the only way to gain the necessary insight into the conditions required for sustained long whisker growth.

Whiskers on Microelectronic Components

Other work at Sandia has addressed the more practical aspects of Sn whisker growth. Many commercial off-the-shelf (COTS) parts are now being supplied with 100% Sn finishes. For high reliability applications, there is a concern for Sn whisker growth during long-term service. Several programs have been initiated to evaluate these devices for actual hardware use. One method to determine whisker susceptibility is through accelerated aging using thermal cycling. It has been recognized that thermal cycling can induce whisker growth and so it has been incorporated into whisker test standards.[11,12] A whisker mitigation method is to assure that the surface finish is contaminated with Sn-Pb or other solder alloys during the solder attachment process to a circuit board. The alloyed surface finish is much less susceptible to whisker growth than is pure Sn. Figure 4 exhibits leadless chip capacitors that have been soldered using SAC305 Sn-Ag-Cu solder. During soldering, the solder flows and forms a fillet to an appreciable height on the end of the capacitor. However, it is difficult to wick the solder upward to cover the entire

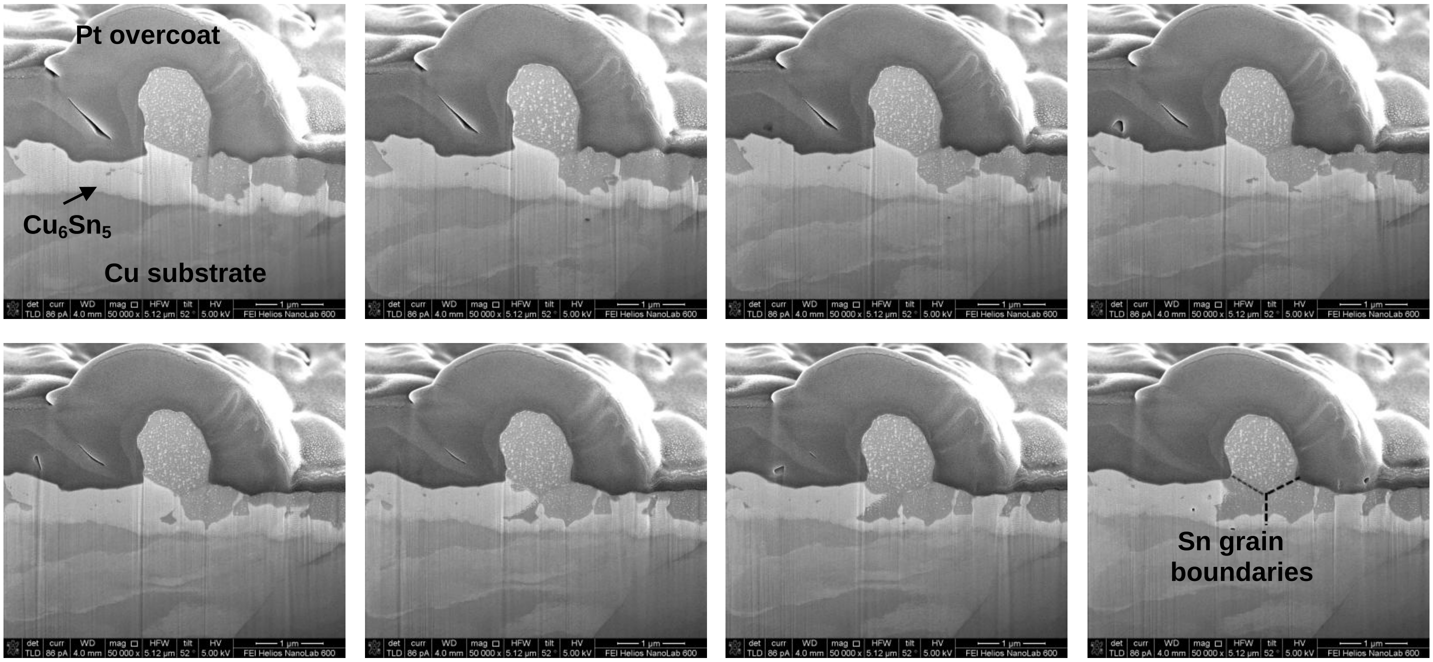


Figure 3. FIB/SEM serial sections part way through a tin whisker. Note the complicated morphology of the IMC layer. The Pt overcoat is applied as part of the FIB process and the white spots in the Sn are redeposition artifact from FIB.

conductive surface. Figure 5 shows SEM photos of a capacitor after 750 thermal cycles between -55 and +125˚C. Only short "stubble" whiskers have formed after this, quite aggressive, thermal cycling. Note that the whiskers/hillocks are only found in the unalloyed pure Sn regions that remained after soldering. These short whiskers would easily pass the requirements (45 μm or shorter) for Class 2 components in JESD 201 standard [12], thereby allowing the components to be acceptable for high-reliability applications. Alternatively, if surface finishes are suspected to be whisker-prone, a solder-dipping procedure (pre-tinning) can be applied to the component leads to remove the pure Sn finish. This process ensures that the entire lead no longer has a pure Sn finish prior to attaching the components to the board. While this technique provides a good whisker mitigation strategy, it is costly and requires labor intensive operations.

Conclusions

This brief overview illustrates the complexity of the Sn whisker growth phenomenon. Research projects at Sandia have concentrated on both defining a metallurgical process for whisker growth as well as characterizing the microstructure of Sn whiskers and surrounding grains. Through this work, the morphology, growth kinetics, and predominant crystallography have been determined for Sn whiskers. A new technique that is being developed to further our understanding of this phenomenon combines serial FIB sectioning with EDS and EBSD analyses. Finally, several practical whisker test procedures and whisker mitigation techniques have been described. These methods must be part of an overall Sn whisker mitigation strategy for any high-reliability Sn-Pb and Pb-free microelectronics production process.

Acknowledgments

The authors are thankful to Mr. Jamin Pillars for electroplating many Sn films and Mr. Michael Rye is acknowledged for FIB sectioning expertise. Thanks also to Ms. Bonnie McKenzie for expert SEM analyses. And thanks to Ms. Pierrette Gorman for collaboration in capacitor testing.

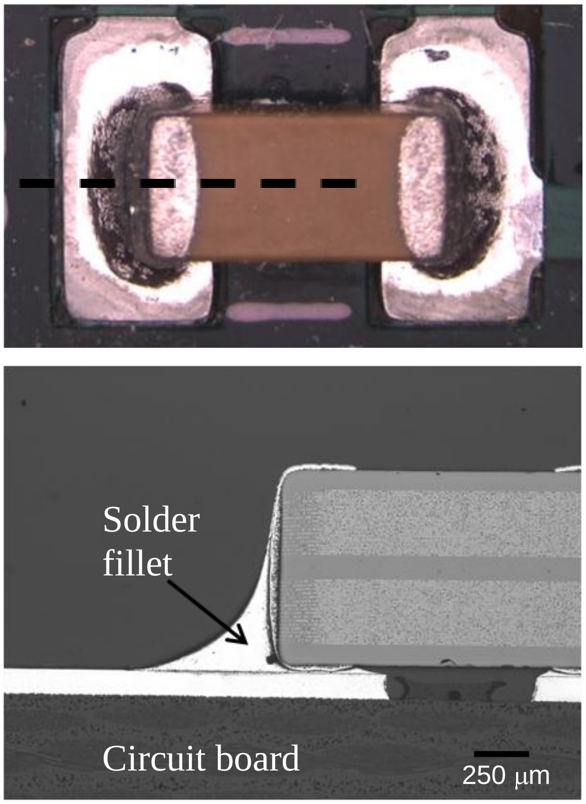


Figure 4. (top) Macro photo showing cross-sectional plane through a leadless capacitor. (bottom) Metallographic cross-section showing solder fillet.

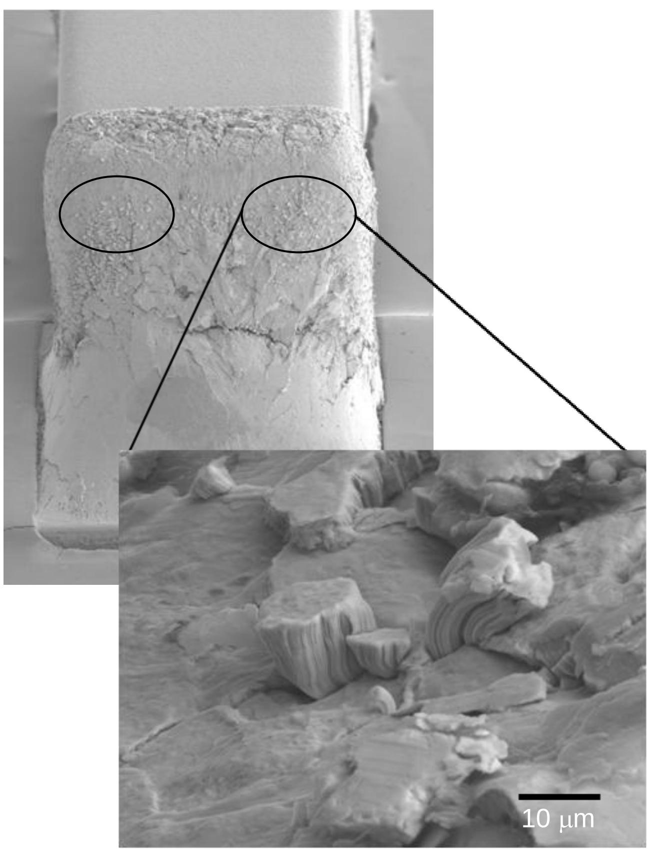


Figure 5. SEM photos showing short "stubble" whiskers after 750 thermal cycles -55 to +125˚C.

References

[1] NASA Goddard Space Flight Center Tin Whisker Homepage, website http://nepp.nasa.gov/whisker/

[2] Boettinger, W.J. et al, "Whisker and Hillock Formation on Sn, Sn-Cu, and Sn-Pb Electrodeposits", *Acta Mat.*, Vol. 53, (2005), pp 5033-5050.

[3] Williams, M.E. et al, "Hillock and Whisker Growth on Sn and SnCu Electrodeposits on a Substrate Not Forming Interfacial Intermetallic Compounds", *J. Elect. Mat.*, Vol. 36, No. 3, (2007), pp 214-219.

[4] Vianco, P.T. and Rejent, J.R., "Dynamic Recrystallization (DRX) as a Mechanism for Sn Whisker Development. Part I: A Model," *J. Elect. Mat.*, Vol. 38, (2009), pp. 1815 – 1825.

[5] Vianco, P.T. and Rejent, J.R., "Dynamic Recrystallization (DRX) as a Mechanism for Sn Whisker Development. Part II: Experimental Study," *J. Elect. Mat.*, Vol. 38, (2009), pp. 1826 – 1837.

[6] Osenbach, J.W., "Tin Whiskers: An Illustrated Guide to Growth Mechanisms and Morphologies", *JOM*, Vol. 63, No. 10, (2011), pp 57-60.

[7] Susan, D.F. et al, "Tin Whiskers: Electron Microscopy and EBSD Characterization", *Microsc. Microanal.*, Vol. 16, Suppl. 2, (2010), pp 792-793.

[8] Panashchenko, L. and Osterman, M., "Examination of Nickel Underlayer as a Tin Whisker Mitigator", *IEEE Elect. Comp. Tech. Conf.*, (2009), pp 1037-1043.

[9] Michael, J.R. et al, "Crystallographic Characterization of Whiskers Using EBSD", *Microsc. Microanal.*, (2011), pp 392-393.

[10] Galyon, G.T. and Palmer, L., "An Integrated Theory of Whisker Formation: The Physical Metallurgy of Whisker Formation and the Role of Internal Stresses", *IEEE Trans. Elect. Pack. Manuf.*, Vol. 28, No. 1, (2005), pp 17-30.

[11] JESD22 A121 2008, "JEDEC Standard: Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes", JEDEC Solid State Technology Association, (2008).

[12] JESD201A,"JEDEC Standard: Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes", JEDEC Solid State Technology Association, (2008).