IEC TR 60068-3-82

Edition 1.0 2024-08

TECHNICAL REPORT

colour inside

Environmental testing –
Part 3-82: Supporting documentation and guidance – Confirmation of the performance of whisker test method

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC TR 60068-3-82 has been prepared by IEC technical committee 91: Electronics assembly technology. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
91/1957/DTR	91/1967/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 60068 series, published under the general title *Environmental testing*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn, or
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ENVIRONMENTAL TESTING –

**Part 3-82: Supporting documentation and guidance –
Confirmation of the performance of whisker test method**

1 Scope

This part of IEC 60068, which is a Technical Report, provides technical background information on the whisker test methods from IEC 60068-2-82 and guidance on test selection.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60068-2-82:2019, *Environmental testing – Part 2-82: Tests – Test XW1: Whisker test methods for components and parts used in electronic assemblies*

IEC 61190-1-1, *Attachment materials for electronic assembly – Part 1-1: Requirements for soldering fluxes for high-quality interconnections in electronics assembly*

IEC 62483, *Environmental acceptance requirements for tin whisker susceptibility of tin and tin alloy surface finishes on semiconductor devices*

ISO 9454-2:2020, *Soft soldering fluxes – Classification and requirements – Part 2: Performance requirements*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
whisker
metallic protrusion that grows spontaneously during storage or use

Note 1 to entry: Whiskers typically do not require any electrical field for their growth and are not to be confused with products of electrochemical migration. Signs of whiskers include:

– striations in growth direction;
– typically no branching;
– typically constant diameters.

Exceptions are known but are rare and can require detailed investigation.

For the purposes of this document, whiskers are considered if:

– they have an aspect ratio (length/width) greater than 2;
– they have a length of 10 µm or more.

Note 2 to entry: For the purposes of this document, whiskers have the following characteristics:

– they can be kinked, bent, or twisted; they usually have a uniform cross-sectional shape;
– they may have rings around the circumference of the column.

Note 3 to entry: Whiskers are not to be confused with dendrites, which are fern-like growths on the surface of a material, which can be formed as a result of electro(chemical)-migration of an ionic species or produced during solidification.

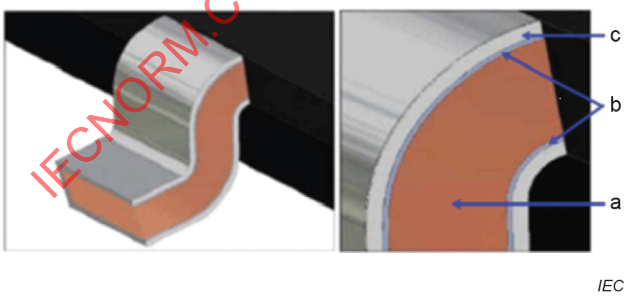
Note 4 to entry: Whiskers are not to be confused with slivers as generated by mechanical metal processing. Whiskers are not to be confused with tubular SnO structures, which may develop under damp-heat test conditions. These structures are hollow and are typically lacking striations occurring on Sn whiskers.

[SOURCE: IEC 60068-2-82:2019, 3.1]

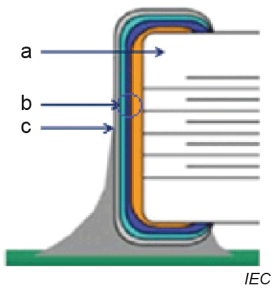
3.2
termination
solderable element of a component consisting of the following elements:

– base material;
– underlayer (or underlayer system, if more than one underlayer is present), if any, located under the final plating;
– final Sn or Sn alloy finish.

See Figure 1.



a) Gull wing termination



b) Chip termination

Key

a base material;

b underlayer (or underlayer system, if more than one underlayer is present), if any, located under the final plating;

c final tin or tin alloy finish.

Figure 1 – Cross-sectional views of component termination surface finishes

3.3
ΔCTE
CTE mismatch
coefficient of thermal expansion mismatch

coefficient calculated by taking the absolute after subtracting the CTE of the base material from the CTE of the surface finish layer:

$$\Delta CTE = | C_f - C_b |$$

where

C_f is the coefficient of thermal expansion of the surface finish layer;

C_b is the coefficient of thermal expansion of the base material

Note 1 to entry: No underlayer system (e.g. Ni, Cu) has any influence on the CTE mismatch.

3.4
mechanical load
load related to the intended mounting/assembly condition of a particular specimen (e.g. press-fit application: stress exerted by the plated through-hole on the press-fit pin), or as a transitional load related to a mechanical process in a trim and form operation to adapt the shape of the specimen to the intended use condition (e.g. bending of a connector pin)

Note 1 to entry: Mechanical load in the context of these test methods is not related to external factors, e.g. thermo-mechanical loads arising from the mismatch of the coefficients of thermal expansion of the various constituents of a particular test specimen upon temperature change.

3.5
classification

3.5.1 Level A
<general electronics products> consumer products, some computer and computer peripherals, and hardware suitable for applications where the major requirement is function of the completed assembly

3.5.2 Level B
<dedicated service electronics products> communications equipment, sophisticated business machines, and instruments where high performance and extended life is required, and for which uninterrupted service is desired but not mandatory

Note 1 to entry: Typically, the end-use environment would not cause failures.

3.5.3 Level C
<high performance electronics products> equipment where continued performance or performance-on-demand is mandatory; equipment downtime cannot be tolerated, end-use environment can be uncommonly harsh, and the equipment shall function when required, such as life support systems and other critical systems

Note 1 to entry: The classification of levels A, B and C is based on IEC 61191-1 [1][1].

[1] Numbers in square brackets refer to the Bibliography.

4 Whisker growth mechanisms

4.1 General

4.1.1 Sn whiskers

4.1.1.1 Features of Sn whiskers

Sn whiskers are metallic protrusions, which can grow spontaneously during storage or use from Sn or Sn alloys. For information on whisker characteristics and their various forms, refer to 3.1 and in IEC 60068-2-82:2019. They can grow up to millimeters, even centimeters long, which is long enough to branch over to a neighboring electrical contact. Being metal growths, this has often led to short circuit failures and system malfunctions. They are not produced during plating (e.g. electrochemical effects during galvanic deposition or dendrite growth), but instead grow afterwards, during storage or use.

4.1.1.2 Sn whiskers growth rate and mechanism

Depending on the conditions, Sn whisker have been observed growing within hours after deposition or first found creating a system failure after 10 years in service, which is why they are often referred to as spontaneous growths. Sn whiskers were already reported as early as 1951 by Compton [2] including the investigation of other metals. Over the last 70 years many contradictory findings have been reported in the literature as well as several whisker theories formed, but still no universal model exists today [3]. However, it is commonly agreed that compressive stress in the Sn film is the fundamental driving force behind whisker growth [4], [5], making whisker growth a stress relief mechanism for the surface finish. Compressive stress sources within the film or applied on the film lead to stress gradients within the deposit, generating atomic migration, which promotes the transportation of atoms to a whisker nucleation site. Migration takes place over long-range diffusion [6] throughout the film, predominately along the grain boundaries, however, also along the surface and interface. As atoms continue to build-up at a nucleation site, a whisker, in return, can grow out of the film, reducing the stress state. In general, all factors that create stress gradients within the film or promote diffusion increase the whiskering tendency.

4.1.1.3 The role of this document on Sn whiskers

Although Sn is not the only metal known to whisker, it is the surface finish of focus for this technical report, since Sn whiskers have been the culprit for many system malfunctions throughout the past and Sn is commonly used in industry due to its beneficial characteristics. Its low melting temperature (231,9 °C) makes it very attractive for soldering applications and its contact resistance, corrosion resistance and low cost has made it, in general, one of the more favorable platings of choice for electronic finishes. The incorporation of lead (Pb) as an alloying element in Sn is the most universally successful prevention method against Sn whisker induced failures. However, due to mandated regulations restricting the use of Pb in electronics [7], [8], the risk of electrical shorts due to Sn whisker growth remains. Still to this day whisker growth characteristics, such as propensity, length and rate are unpredictable, and vary from plating to plating as well as with substrate material. Therefore, it is important to define a set of tests as guidelines to be able to compare and assess the whiskering propensity of different surface finish/substrate combinations in a structured manner. To effectively do this one must first have an understanding for the basic Sn whisker growth mechanisms.

4.1.2 Sn surface finishes

4.1.2.1 General

For all practical industry purposes, Sn is plated through galvanic deposition or hot-dip tinning. Due to the ease using these plating options for Sn and its low material cost, it generally does not deem appropriate to use other more expensive plating techniques such as chemical or physical vapor deposition. Sn alloys are also used depending on application. For information regarding Sn alloys, see also [9].

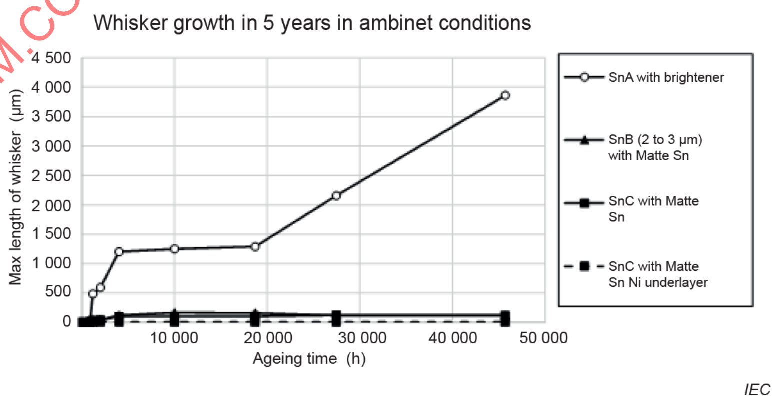
4.1.2.2 Galvanic Sn plating

Galvanic Sn plating is often the method of choice since it offers a larger spectrum of plating possibilities, especially selective plating for other surface finish options on the mating side. The plating can be applied for different geometries as individual piece parts through barrel or rack plating, or in a strip format on a plating line. The electrolytes and therefore, their finishes are mainly divided into two different types: bright or matte. Other than just appearance, the main differences between the two deposit types are smaller grain size and higher carbon (C) content for the bright Sn, typically < 1 µm and > 1 000 ppm C respectively, whereas matte Sn generally has an average grain size of a few microns and < 150 ppm C in the finish, as stated in Table 1 of IEC 60068-2-82:2019. Though bright Sn has an excellent cosmetic appearance, the higher amount of co-deposited C, as a result of the organic brighteners used in the electrolyte, end up creating a higher internal stress in the Sn finish. Carbon in a Sn deposit can be measured using different methods, such as Glow Discharge Optical Emission Spectroscopy [11] or Auger-electron spectroscopy in combination with sputter-depth profiling.

Furthermore, the smaller grain sizes in bright Sn do not help against whisker growth. Smaller grains in general lead to more grains on the surface and the probability for more low index grains, which make for great whisker nucleation sites. Smaller grains also mean additional grain boundaries, which promotes diffusion and easier acccess to a whisker root. For example, a layer with an average grain size of 1 µm has a 1 000x higher diffusion rate than a layer with approximately 10 µm grains. An example of grain size and whisker growth from a bright Sn ("SnA" sulfuric acid base) vs. matte Sn finish ("SnC" MSA base) is given in Figure 2. Here the maximum whisker lengths are compared after 5 years of incubation at room temperature / relative humidity (RT/RH) conditions, where the impact on whisker growth from a bright Sn finish is clear.

Bright Sn **Matte Sn**

a) grain size/orientation



b) whisker growth between a bright Sn deposit and a matte Sn both approximately 2 µm to 3 µm thick

Figure 2 – Grain size and whisker growth on bright Sn and matte Sn finishes [10]

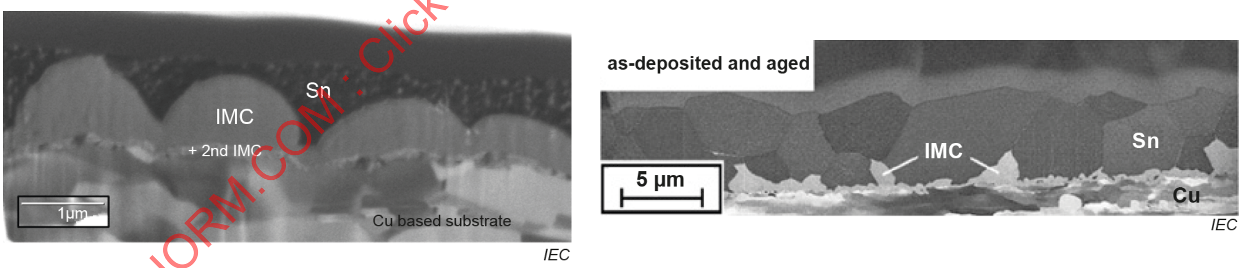
Consequently, matte Sn is usually used for electronic finishes to reduce the internal film stresses and thus, the whisker risk. All galvanic surface finishes discussed throughout the remainder of this chapter will therefore, be based on matte Sn deposits.

There exist numerous different matte Sn electrolytes available on the market today with the majority of them using a methanesulfonic acid (MSA) base. In order to achieve a homogeneous layer thickness throughout the surface and to reduce the redox reaction, different additive systems and an antioxidant are utilized. The design of the electrolytes can be optimized for certain plating "purposes" such as complicated geometry, high plating speed, low plating speed, appearance, plating distribution, etc. To achieve different demanding targets the concentration of the electrolyte components (e.g.: Sn, MSA, and additives) as well as the plating parameters can also be adjusted (e.g.: temperature, current density, and agitation). The whisker propensity for galvanic Sn platings strongly depend on the electrolyte chemistry, process parameters and plating method. Therefore, every component-geometry, plating method, electrolyte and set-up of plating parameters requires a specific assessment and qualification.

4.1.2.3 Hot-dip tinning

Due to the low melting point of Sn (231,9 °C), it can be hot-dip plated. Hot-dip plating is the immersion of the base material into the molten Sn after the surface has been first appropriately prepared (e.g.: cleaning, fluxing), which means that selective plating is not an option for tinning. The molten bath can be easily alloyed, often with Ag and/or Cu and the temperature typically varies between 250 °C and 290 °C depending on alloying elements and process set-up. It is broadly used for mechanical components as pre-plated material, but also for various electronic components. The resultant surface tends to be smooth and shiny.

A significant difference between a Sn finish which is hot-dip plated compared to galvanic plated, especially when regarding whisker growth, is the intermetallic compound (IMC) formation between Sn and Cu based substrate materials, due to the high temperatures needed for tinning, see Figure 3. IMC formation is automatically present in hot-dip Sn deposits, in the as plated state, but not in galvanic plated finishes, which are plated at much lower temperatures typically between approximately 20 °C to 40 °C depending on the electrolyte. The various IMCs between Sn and Cu at different temperatures and their effects on whisker growth are explained below, in 4.2.1.



a) a hot-dip plated Sn finish **b) an electroplated Sn finish**

Figure 3 – Example comparison of IMC formation between a Sn surface deposit and Cu based substrate

4.2 Basic Sn whisker mechanisms

4.2.1 General remarks

As stated in 4.1.1, whiskers grow as a result of compressive stress gradients within the film, which promote Sn atom migration. In the past, the focus tended to lie mainly on the macroscopic stress of the Sn finish. However, macroscopic stress is not the only relevant driving force for whisker formation. In fact, it is the microscopic compressive stress sources, creating microscopic stress gradients throughout the film, which play a significant role in whisker growth [12]. If these factors are present within a certain range, whisker growth can be expected.

The basic stress sources known for generating Sn whisker growth, as well as any combination of them together, include (in no particular order):

a) irregular IMC growth between Cu and Sn, which can vary between Cu-based substrates;

b) corrosion at the Sn surface and/or at the grain boundaries;

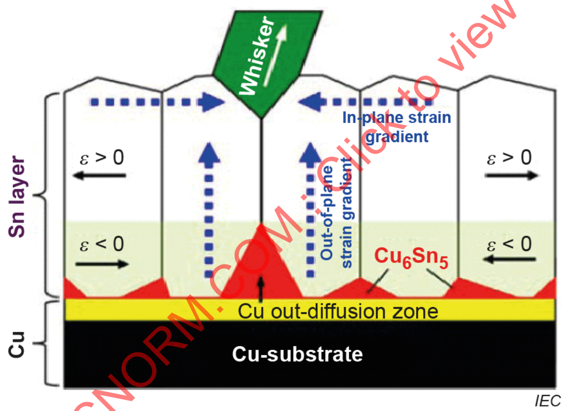
c) coefficient of thermal expansion (CTE) mismatch between base material and Sn surface finish;

d) compressive external mechanical forces on the Sn finish.

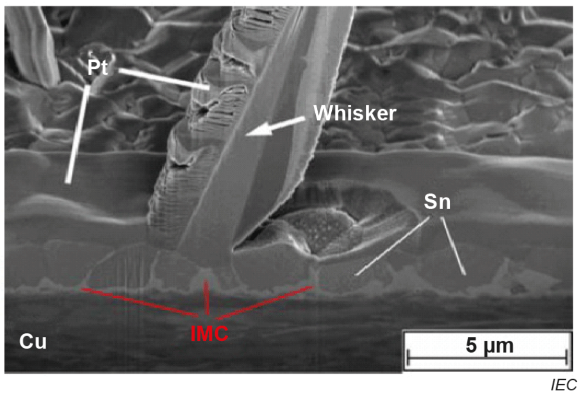
Throughout the following clauses these stresses will be based around galvanic matte Sn finishes. The individual factors will be discussed in greater detail throughout the following sub-clauses. It is evident that the Sn grain orientation as well as shape/size directly influence the whiskering properties of the deposit. Depending on the system as well as its working and environmental conditions, any of these factors can take precedence over the other when it comes to whisker growth.

4.2.2 IMC growth

Sn and Cu react with one another at ambient room temperature (RT) conditions, forming an irregular IMC, Cu_6Sn_5, through Cu diffusion into the Sn grain boundary. This IMC formation is accompanied by a specific volume increase, resulting in a residual compressive stress in the depth of the Sn coating where the IMC forms due to the constraint imposed by the substrate [13]. Such localized stress sources create stress gradients (compressive stress by the IMC and tensile by the surface), resulting in Sn-atom diffusion away from the area where the IMC is formed. The stress gradients exist vertically in the Sn layer towards the surface, as well as horizontally in the surface. An illustration of the situation is shown in the following Figure 4 a) compared to a FIB cut from an actual matte Sn film deposited on Cu based substrate in b), where a whisker is growing out of the surface directly in the area of one of the high IMC stressed locations. The columnar grains seen here are typical for matte Sn finishes.



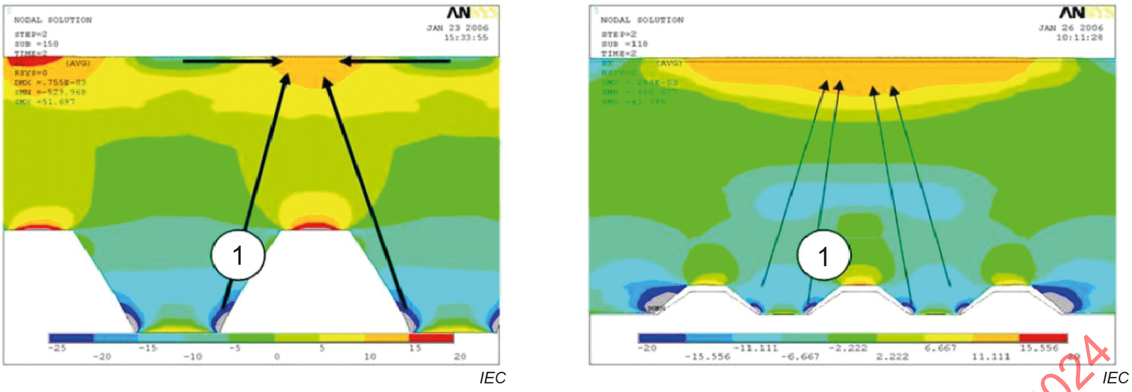
a) Schematic illustration of the presence of the stress gradients in the Sn layer due to the formation of irregular IMC (Cu_6Sn_5)



b) a FIB-cut of Sn on Cu-alloy

Figure 4 – Whisker formation in Sn layer [14]

A modulation of the stress distribution will be established because of the certain grain size, leading to hot spots (intensive source of vacancies) near the surface, creating tensile stress. Figure 5 shows a FEM simulation of the stress formed due to the irregular Cu_6Sn_5 IMC growth in a 5 µm thick a) and 10 µm thick b) Sn finish [15]. Here the stress flow in a Sn finish can be clearly seen – from the compressive stress due to the IMC formation to the tensile stress on the surface – explaining the stress gradients and Sn atom migration to a whisker root near the surface. From these simulations, it is clear that thicker Sn layers result in smaller stress gradients and less localized tensile stressed, hot spots at the surface. Instead, the size of the hot spots are larger and wider, meaning a larger volume where the Sn can be redistributed, leading to a reduction in whisker lengths and therefore, risk of whisker induced failure as well.



a) **5 µm thick** b) **10 µm thick**

Figure 5 – Stress gradients in Sn layer [15]

As a result of this irregular RT Cu_6Sn_5 IMC growth and its effect on whisker growth, where these occur, it is crucial to carry-out ambient whisker tests, as depicted in 5.1, Figure 2 and details described in 6.1 of IEC 60068-2-82:2019. Since whiskers grow as a stress relief mechanism for the Sn finish, the growth tends to eventually saturate at some point over time. Different deposits have different saturation tendencies depending on their grain size/orientation, grain growth/recrystallization, IMC formation, etc. For practical comparison of the whiskering propensity between Sn finishes, 4 000 h was chosen for ambient tests as described in IEC 60068-2-82:2019, 6.1. An example is given in Figure 6. However, this does not guarantee that all Sn whisker growth is completed, for example, refer to Figure 14.

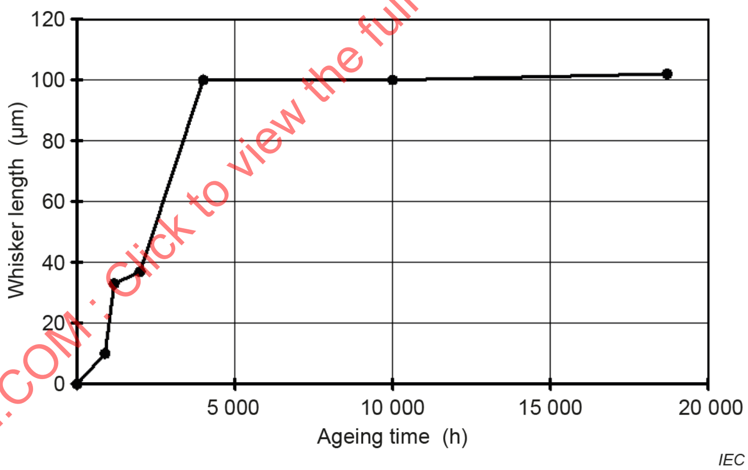
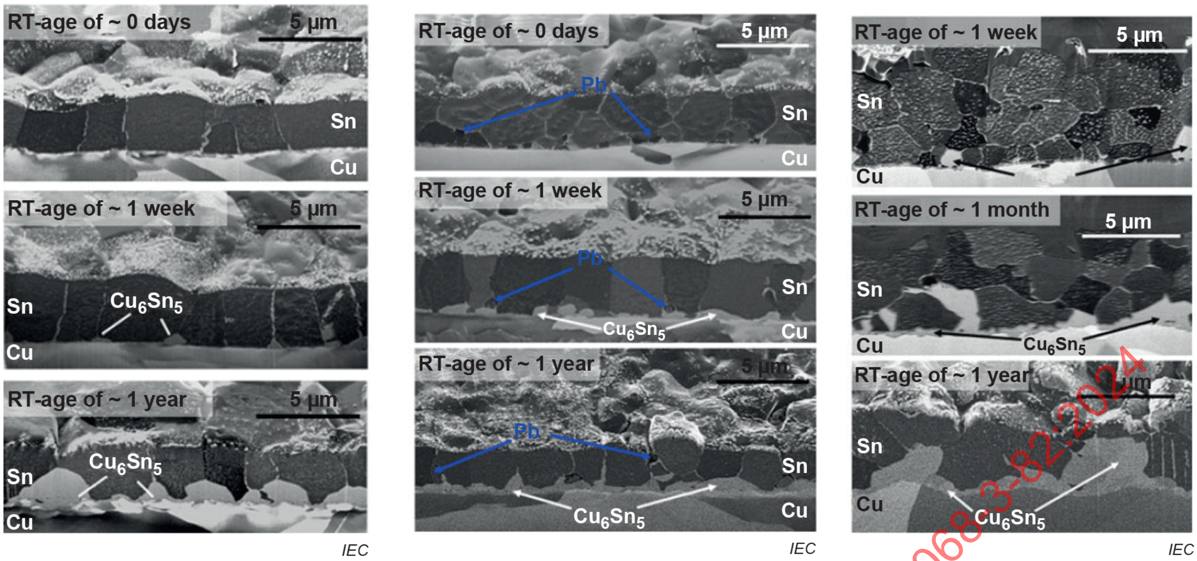


Figure 6 – An example of whisker growth (length) from approximately 2,5 µm matte Sn plated on Cu aged at ambient conditions (RT/RH)

One method to effectively counteract whisker growth due to irregular IMC formation is to implement a way to redistribute the stress gradients in the Sn layer. The average columnar grains deposited from typical matte Sn electrolytes cannot redistribute the stress effectively in the Sn matrix, since diffusion takes place along the grain boundaries. Here equi-axed or globular grains would be very useful. In fact, before the restrictions on Pb, when SnPb galvanic platings were utilized, the grains in the SnPb deposits were globular, which helps explain why SnPb platings did not result in Sn whisker induced failures. However, this is not the natural tendency for pure matte Sn deposits, but such a structure could be produced by manipulating the plating parameters and/or adjusting the electrolyte. Figure 7 c) shows just such a case where the Sn deposit was manipulated in lab (beaker glass) into a more globular structure and compares it to the typical columnar matte Sn a) as well as SnPb b) grain structures [5]. Here the columnar Sn grains a) and globular Sn grains c) where both deposited from the same electrolyte. Only the plating parameters were changed.



a) **normal columnar Sn**

b) **SnPb**

c) **manipulated globular Sn on Cu at different time periods after plating to compare grain growth and IMC formation over time**

Figure 7 – Microstructures of different Sn and SnPb surface finishes [5]

Ambient whisker tests were carried out on all 3 variations. After 1 year of incubation at RT/RH conditions no whiskers could be found from the SnPb or globular Sn samples. However, the columnar Sn finish produced whiskers up to 500 µm long. This demonstrates why it is crucial that even if just a plating parameter is changed, the resultant Sn deposit needs to be tested and re-qualified.

In Figure 7 it is clear, that the globular grains grow over time, whereas the columnar grains do not. It is also noticeable that the IMC formation for both pure Sn films is comparable in intensity. From the IMC formation point of view, one could expect a similar response for the whisker growth, but this is not the case. The imposed compressive stress due to irregular IMC formation could be redistributed not only vertically, but horizontally as well, by the system with a more globular grain structure. The energy from the irregular IMC induced compressive stress is used for internal grain growth instead of whisker growth, as Sn atoms are no longer limited to only vertical diffusion to the surface. This was not the case for the columnar grain structure, where the only diffusion paths in the Sn layer are directly from bottom to the top, promoting whisker growth out of the surface. The IMC in the SnPb plating is not as pronounced as by the pure Sn films. Since the solubility of Pb in Sn is < 1 %, nearly all Pb collects in the grain boundaries, which also helps against Sn whisker growth, since it blocks-up some of the diffusion pathways for the Sn atoms.

The overall stress state of these samples was also investigated over time using high resolution XRD, as shown in Figure 8 a), b) and c), along with the stress profile of each as a function of depth into the finishes through synchrotron measurements d). Positive values correspond to tensile stress and negative values are compressive. In Figure 8 d) the stress gradients within the films are modulated, depending on the grain size, and establish a tensile stress on the surface (source of vacancies), which is in agreement with the FEM simulation discussed above. However, the columnar finish clearly has the largest stress gradients from interface to surface, since its stress distribution capabilities are limited compared to the globular grains. The build-up of compressive stress over time in Figure 8 a), b) and c) is occurring in all finishes, but the compressive stress is visibly reduced in the SnPb and globular Sn structure, resulting in flatter stress progressions due to the observed grain growth above.

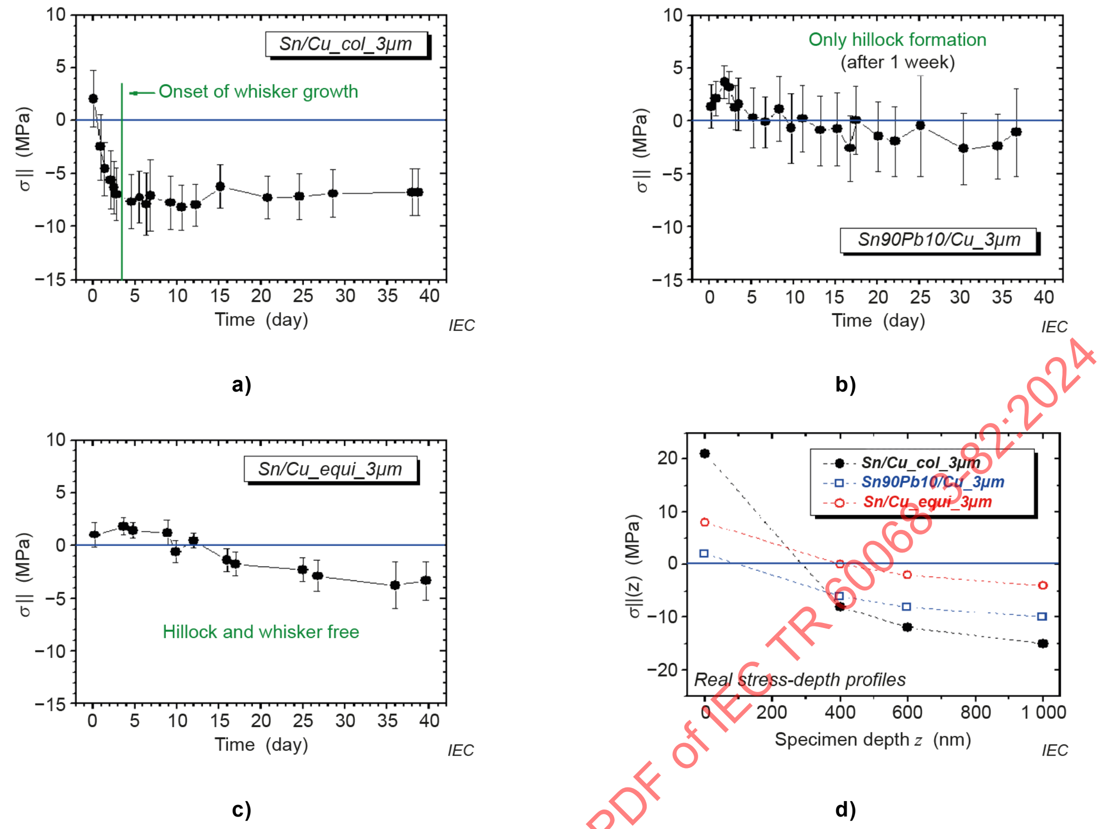


Figure 8 – Stress states of different Sn and Sn/Pb surface finishes [5]

Although this technique works well and helps explain the different mechanisms responsible for whisker growth, manipulation of a galvanic Sn deposit in mass production (e.g.: plating line) is not realistic.

Alternative methods to avoid the built-up of compressive stress gradients due to irregular Cu_6Sn_5 growth would be to incorporate a diffusion barrier between the Cu and the Sn to prevent the IMC from ever forming. Such a layer can be made using the materials and processes given in Table 1.

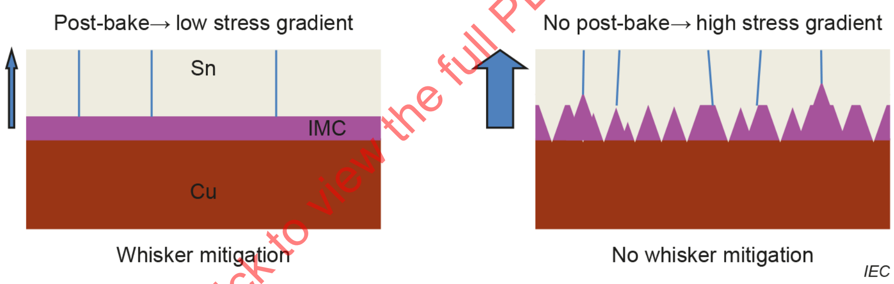
Table 1 – Materials used for a diffusion barrier along with their typical thickness, process parameters and quality criteria.

Material	Thickness [µm]	Process parameter
Cu_3Sn IMC	≥ 0,5 (typical: 0,7)	Minimum 1 h at minimum 150 °C (annealing/Postbake) or thermodynamic equivalent (e.g.: 10 min at 180 °C)
		Reflow of the Sn layer
		Hot-dip tinning
Ni	≥ 0,5 (typical: 1,0 – 2,0)	Galvanic plating, dense layer, high ductility

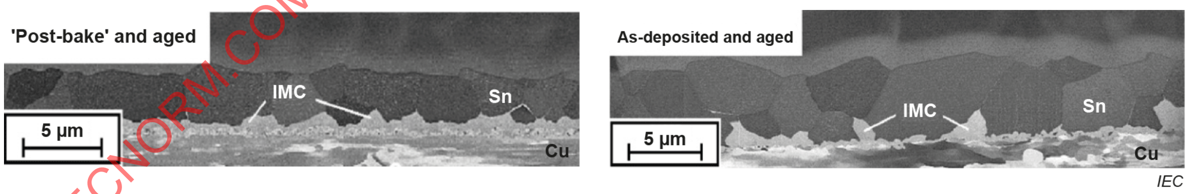
At higher temperature exposures (≥ 60 °C) Sn and Cu start forming a second IMC, Cu_3Sn, between the Cu_6Sn_5 and Cu-based substrate. Unlike the Cu_6Sn_5 compound, the Cu_3Sn grows much more regular and offers a good barrier layer, which helps prevent the irregular Cu_6Sn_5

IMC from growing further at RT conditions by blocking the Cu in the substrate from diffusing into the Sn finish. A post-heat treatment can also help relieve residual stresses in the Sn finish. A simple schematic is given in Figure 9 a) for illustration purposes along with scanning electron microscope (SEM) images of FIB cuts in b) post-heat treated (150 °C for 1 h) "specimen II" on the left, compared to as plated "specimen I". Specimen I + II both are both approximately 3 µm to 4 µm of matte Sn plated from the same electrolyte under identical conditions on Cu substrates.

“Specimen II” on the left is post-heat treated. These specimens will be discussed in the following three figures. As depicted within the FIB cut of the post-heat treated “specimen II” in Figure 9, , at higher temperature exposures, there is grain growth, which reduces the number of diffusion pathways (e.g. grain boundaries) for the Sn atoms, making it more difficult to reach a whisker nucleation site [16]. The higher the temperature, the faster and more regular a continuous Cu_3Sn layer can be produced, since at higher temperatures, bulk diffusion comes into play and eventually takes over grain boundary diffusion; $\sim T/T_{melting} \geq 0,7$ so for Sn ~150 °C. However, for this to be beneficial it is ideal that the Cu_3Sn is formed before the Cu_6Sn_5 IMC begins growing in the grain boundaries and creating stress sources in the Sn layer. For this reason, it states in Table 1 of IEC 60068-2-82:2019 that the annealing process is to be carried-out within 24 h after galvanic deposition. The resultant stress state as a function of time and depth between the post-heat treated specimen compared to as plated is given in Figure 10 [16]. The annealing or post-heat treatment prolongs the residual compressive macrostress build-up in the Sn film over time by delaying formation of the Cu_6Sn_5 IMC through the Cu_3Sn barrier compound, as well as reduces the stress gradients towards the surface even after several months at RT aging. Whiskers were observed on specimen I after 240 h of RT exposure, about 40 h after plateauing at a compressive stress of -8 Mpa, whereas no whiskers were detected on specimen II even after 5 200 h of aging.

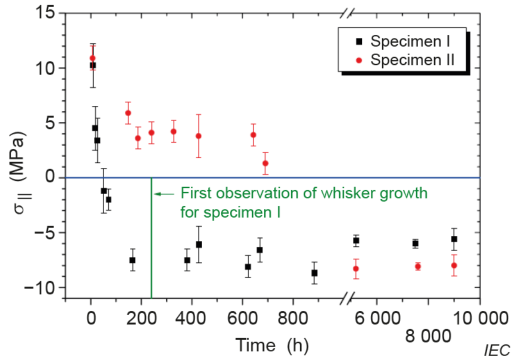


a) Schematic of regular IMC formation due to post-heat treatment on the left ("specimen II") compared to none on the right ("specimen I")

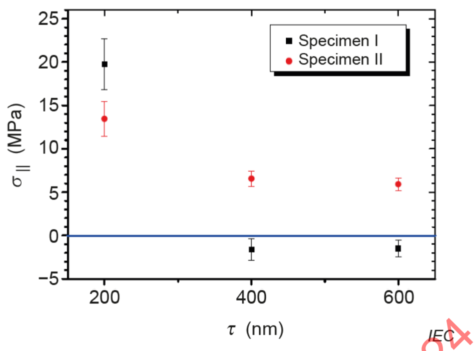


b) SEM images of a FIB-cut on galvanic Sn after post-heat treatment on the left compared to as plated on the right

Figure 9 – Effect of post-bake heat treatment on microstructure and stress gradients [16]



a) Stress state upon aging at room temperature for a specimen without post-bake heat treatment (specimen I) and with post-heat treatment (specimen II)

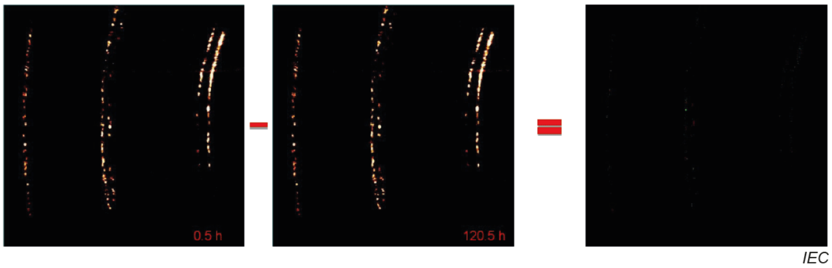


b) Stress state as function of penetration depth in X-ray stress analysis for a specimen without post-bake heat treatment (specimen I) and with post-bake heat treatment (specimen II)

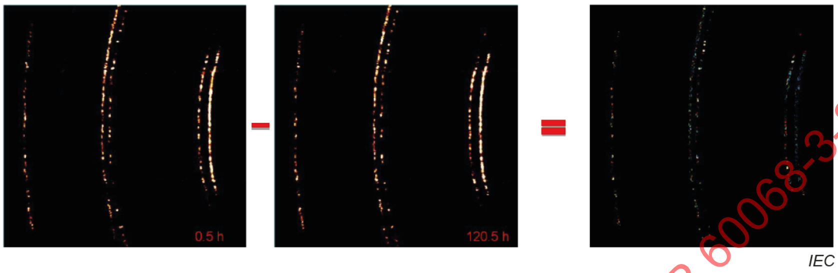
Figure 10 – Stress states of different Sn surface finishes [16]

Another possibility is melting the Sn finish after plating by running it through a reflow process. Although annealing has been found to have a significant mitigating effect on whisker formation for a wide range of Sn film thicknesses on various substrate materials [17], [18] (see Figure 10 for example), reflowed specimens have been found to not show any observable whisker growth from approximately 3 µm Sn finishes on Cu, even after bending and additional heat aging [19]. In addition to a residual stress relief mechanism found during post-heat treatment, reflow can also change columnar grain structures to equiaxed in regions, resulting in lower grain boundary diffusion rates [20]. However, when melting Sn, the surface tension automatically tends to minimize its surface area, which can lead to blisters or even dewetting of the Sn film after reflow, depending on multiple variables including the accessible free Sn (i.e. film thickness). Therefore, annealing is still the preferred method for thicker Sn films (minimum 7 µm) and reflow for thinner deposits. According to results from [21] after annealing Sn plated electromagnetic relays at 140 °C for 0,5 h to 3 h, annealing had markedly better Sn mitigating effects on thicker Sn films (approximately 10 µm) compared to thinner (approximately 2 µm).

An additional influential outcome regarding post-heat treatment/reflow against whisker growth, is the retardation of crystal growth after heat treatment [17], also referred to as the pinning effect. This has been observed by tracking Sn crystal reflection spots over time within the first week of RT exposure using 2D x-ray diffraction (XRD) on the samples discussed above: "specimen I" and "specimen II" (as plated Sn and post-heat treated Sn respectively) [22]. By changing the frame rotation, different grains have lattice planes in the reflection. The appearance/disappearance of reflection spots as well as change in intensity provide evidence of movement and diffusion in the Sn deposit, which promotes whisker growth. Figure 11. compares XRD results after a 120 h interval from the post-heat treated specimen as shown in Figure 11 a) and the specimen as plated as shown in Figure 11 b). In Figure 11 a) it is clear that the microstructure of the post-heat treated specimen is stable, while the as plated specimen in Figure 11 b) reveals multiple changes in reflection spots before the onset of whisker growth [22].



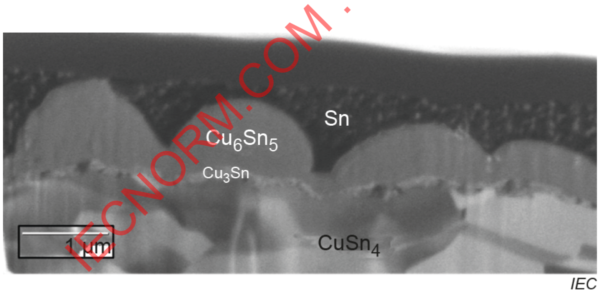
a) post heat-treated Sn on Cu



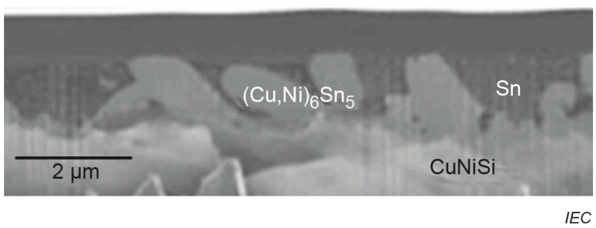
b) as plated

Figure 11 – 2D-XRD analysis of Sn surface finishes [22]

After understanding IMC formation between Cu and Sn at different temperatures and their effect on whisker growth, it is easier to understand why hot-dip plated finishes do not possess the same whiskering characteristics as galvanic deposits and therefore, do not require any extra post-heat treatments for whisker prevention. Since they have already been exposed to higher temperatures during plating, they have the corresponding developed IMC formation and/or pinned grains, which mitigate Sn whisker growth. Hot-dipped Sn on CuNiSi (copper-nickel-silicon) substrates, for example, do not commonly produce a regular, continuous Cu_3Sn IMC barrier layer in as plated condition. However, they still possess Sn whisker mitigating properties due to the Sn grain pinning from the heat exposure during deposition. Due to Ni in the substrate material, a $(Cu,Ni)_6Sn_5$ compound is formed instead of Cu_6Sn_5, which moderates the formation of Cu_3Sn (see Figure 12). Nevertheless, it is important to remember, as mentioned above, that different substrate materials can also affect the whisker propensity.



a) a CuSn4 – Cu_6Sn_5 and Cu_3Sn IMC formation

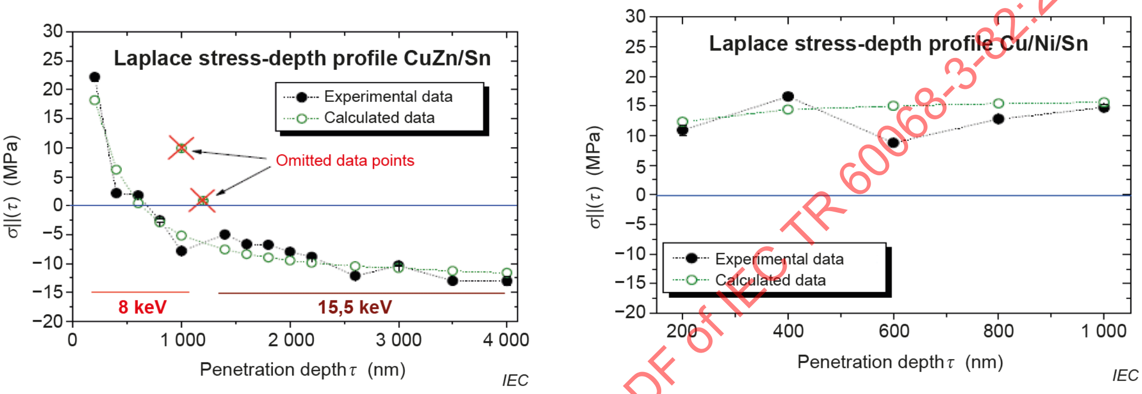


b) CuNiSi substrate material – $(Cu,Ni)_6Sn_5$ IMC formation

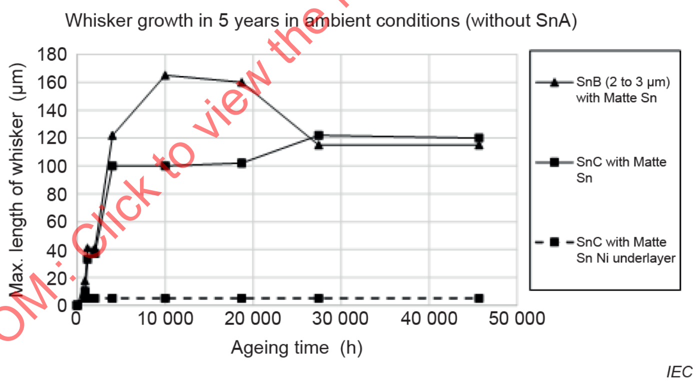
Figure 12 – IMC formation of Sn surface finishes

If a post-heat treatment or reflow process is not desired, an extra barrier layer can be separately deposited to prevent RT IMC growth between Sn and Cu. Ni is a great barrier layer for Cu based substrates in general and the most frequently used for Sn whisker mitigation due to its effectiveness. Therefore, it is given in Table 1 of the IEC 60068-2-82:2019 as the barrier of choice.

Important for the functionality and effectiveness of the diffusion barrier is the existence of a continuous, closed barrier layer. Therefore, at least 0,5 µm is generally used for the barrier layer thickness. The difference a barrier layer provides against stress build-up and whisker growth can be seen and compared to a Sn system without a barrier layer in Figure 13 a) and b) through high resolution XRD measurements of the stress state in the film systems as well as whisker growth results after 5 years of RT/RH exposure [12]. Example given here is a Ni barrier layer. Figure 13 a) shows the stress progression within a Sn film where no barrier layer is implemented on the left compared to with a Ni barrier layer on the right. With the Ni barrier layer the stress gradients from interface to surface are minimized and that no compressive stress is built-up around the interface, which coincides with the whisker results in Figure 13 b) from a separate test also using Ni as a barrier layer. After 5 years of ambient conditions, the specimen with the Ni barrier layer (dotted line) has grown no whiskers, while the specimens without a barrier layer have both produced whiskers > 100 µm long.



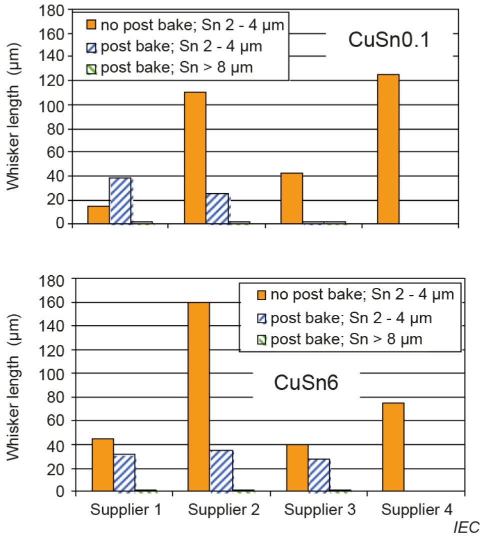
a) Depth profile of the compressive stress levels of matte Sn finishes without and with a Ni barrier layer



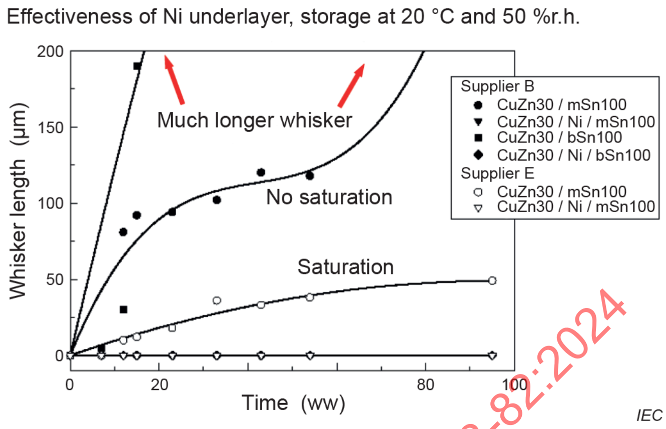
b) Whisker growth from a separate test without and with a Ni barrier

Figure 13 – The compressive stress levels of matte Sn finishes without and with a Ni barrier and the corresponding whisker growth [12]

An exemplary overview of whisker lengths regarding several of the influencing factors discussed above is provided in Figure 14. Figure 14 a) compares the influence of base material and bath supplier (i.e.: Sn electrolyte) on whisker growth after 21 weeks of RT aging with and without an annealing process of 180 °C for 5 min. It is clear that each electrolyte along with its corresponding plating parameters has a different whiskering tendency. Here the general effects of a post-heat treatment ("post bake") can also be seen, especially in combination with a thicker Sn deposit. Substrate differences can also be observed. Figure 14 b) depicts results from matte ("mSn100", 2 different suppliers) and bright ("bSn100") Sn platings on CuZn30 base material with and without a Ni barrier layer. The effectiveness of a Ni layer against whisker growth is evident as well as the whiskering properties between electrolytes from different suppliers.



a) Influence of base material, electrolyte supplier and annealing process on whisker growth



b) A Ni barrier layer and differences in whisker growth saturation

Figure 14 – Whisker growth with several factors and saturation with a Ni barrier [23], [24]

4.2.3 Corrosion

The reason Sn corrosion is a relevant factor for whisker growth can be understood, if one considers the increase of volume due to the formation of Sn's oxidation products, SnO and SnO_2. The volume increase for the reaction from Sn to Sn oxide and Sn dioxide has been calculated by to be about 29 % for SnO and 34 % for SnO_2 [26]. Similar to RT grain boundary IMC formation, excess of these oxide products as well as Sn hydroxides penetrating into the film can create stress sources within the Sn film, however emanating from the surface of the Sn deposit instead of at the finish/substrate interface. A simple schematic of such oxidation/corrosion products forming on the Sn surface and their stress effects in the film regarding whisker growth is given in Figure 15. For the same reasons as previously discussed, a globular grain structure is helpful to redistribute the resultant stress gradients and reduce whisker growth.

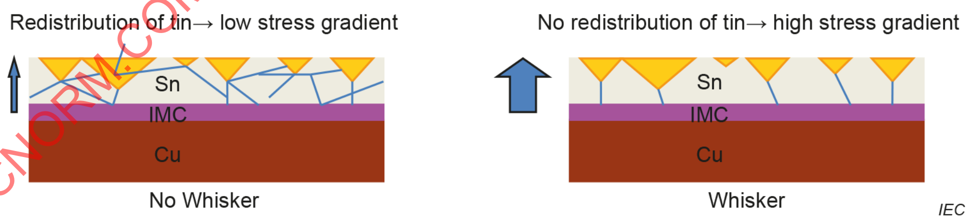


Figure 15 – Schematic of corrosion stress in a Sn film and its redistribution capabilities

In general, Sn is a material with good resistivity against corrosion. Sn creates a very thin, stable oxide layer in atmospheric conditions of up to approximately 5 nm. The oxide layer is not known to excessively grow further into or through the Sn finish on its own unless exposed to temperatures approaching the melting point of Sn (≥ 200 °C) or to superheated steam or higher humidity conditions in combination with elevated temperature. In a Sn oxidation investigation carried-out by Auburn University [27] sputtered Sn films (approximately 2 µm) and bulk Sn were exposed to various dry heat O_2 environments ranging from 100 °C-215 °C for different time intervals starting at 1 h and going to up 40 h, as well as H_2O steam at 121 °C for 12 h (autoclave). The resultant oxide formation was analysed using high resolution X-ray photoelectron, Auger electron, Rutherford backscattering and Raman scattering spectroscopy. Only a very thin, native oxide layer was found for all dry heat O_2 exposures up to 150 °C of approximately 100 ± 50Å regardless of aging time. At temperatures ≥ 200 °C (approaching melting point of Sn) were the 2 µm Sn films found to be completely penetrated by oxygen, with increasing oxygen content the longer the exposure time. Whereas no discernible oxygen was found in any of the bulk specimens after dry heat O_2 aging, which can be due to the difference in grain structure and vacancy opportunities for oxygen diffusion. However, both bulk Sn and sputtered Sn films were found to be oxidized after steam aging. Similar results have also been observed from galvanic matte Sn after several hours of exposure at 150 °C, where no increase of the Sn oxide layer could be found [28]. It seems evident that for through oxidation or corrosion of Sn at normal working temperatures (≤ 130 °C), moisture of some kind is key, especially in combination with elevated temperatures. In two separate studies from Oberndorff [29] and Su, corrosion on galvanic Sn platings after exposure to 60 °C and 93 %RH was observed. Both recorded whisker growth in or directly near the corroded regions.

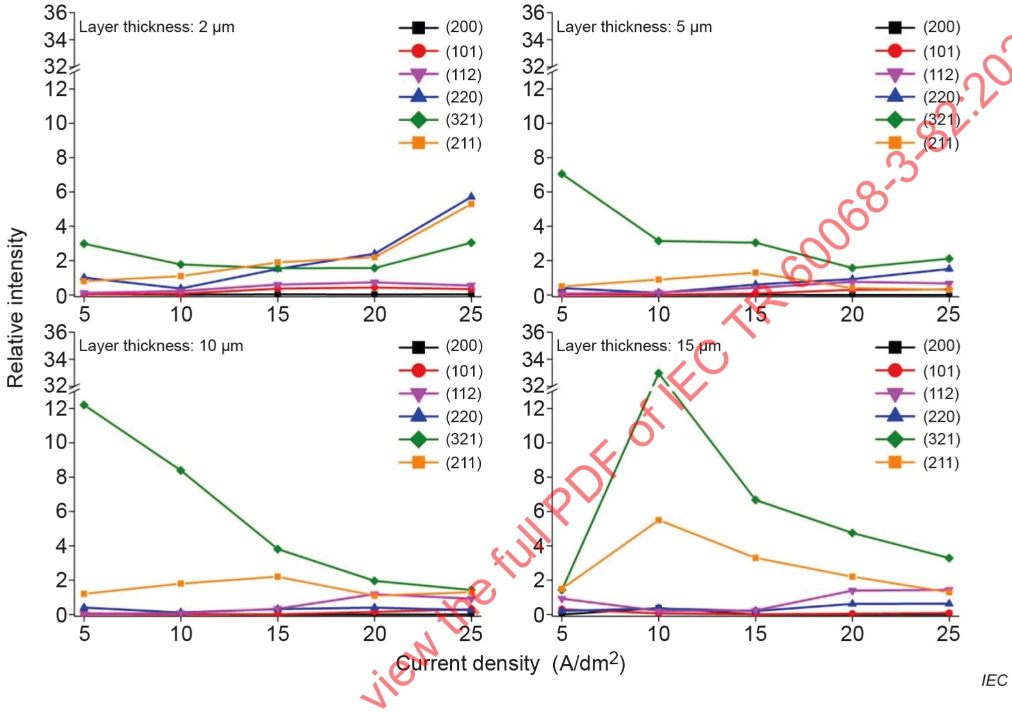
Due to the evidence that Sn whisker can grow as a result of corrosion and since the driving mechanism behind corrosion is the difference in the chemical potential (e.g. between grain orientation, type of intermetallic, base material, etc.) where, as seen in Table 2, Sn is less noble than most of the used elements in electronic systems (i.e.: Sn is most likely to be oxidized first), whisker corrosion tests are relevant and need to be investigated.

Table 2 – Standard electrical potential for selected chemical elements

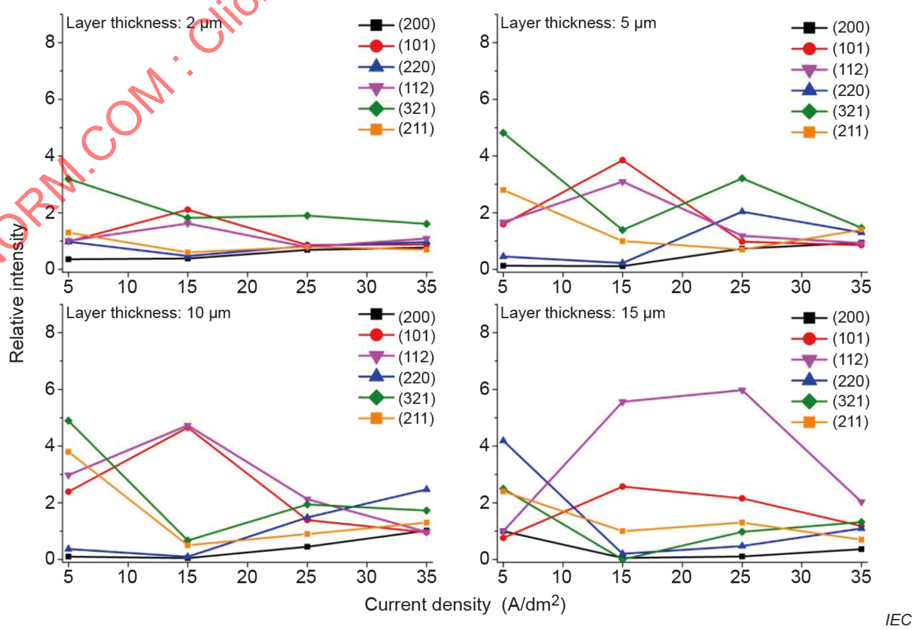
Oxidant	Reductant	Potential [V]
$Sn + 4H^+ + 4e^-$	SnH_4	-1,07
$Zn^{2+} + 2e^-$	Zn	-0,762
$Ni^{2+} + 2e^-$	Ni	-0,25
$Sn^{2+} + 2e^-$	Sn	-0,132
$Pb^{2+} + 2e^-$	Pb	-0,127
$SnO + 2H^+ + 2e^-$	$Sn + H_2O$	-0,10
$SnO_2 + 2H^+ + 2e^-$	$SnO + H_2O$	-0,09
$Sn^{4+} + 2e^-$	Sn^{2+}	+0,15
$Cu^{2+} + 2e^-$	Cu	+0,34
$Cu^+ + e^-$	Cu	+0,52
$Ag^+ + e^-$	Ag	+0,799

In the workframe of the iNEMI project, it was often mentioned that they could observe a clear lot dependence of the sample with respect to whisker growth [31]. Since Sn whisker growth is very dependent on grain structure/orientation, which varies between electrolyte, plating parameters and film thickness, along with the observed grain structure dependence on Sn oxidation, it is best to consider a deep dive investigation on the relation between the grain orientation and corrosion propensity of galvanic Sn surface finishes.

Here Eckold [32] did the first detailed investigation, testing 4 different Sn electrolytes at varying current densities/film thickness and then analyzing their grain orientation, corrosion propensity and whisker growth. All Sn finishes were deposited on pure Cu substrates. Directly after plating the specimens were subjected to a post-heat treatment for 1 h at 150 °C. The grain orientation was measured using X-ray diffraction for each deposit. Corrosion tests were carried-out through contamination by immersing the samples for 20 min in a 0,1 M NaCl water solution, followed by air drying and then aged for 200 h at 80 °C and 80 % RH. Figure 16 shows the grain orientation results for Figure 16 a) electrolyte 2 and Figure 16 b) electrolyte 3 at various current densities and film thicknesses.



a) **Grain orientation of Sn deposits from electrolyte 2**

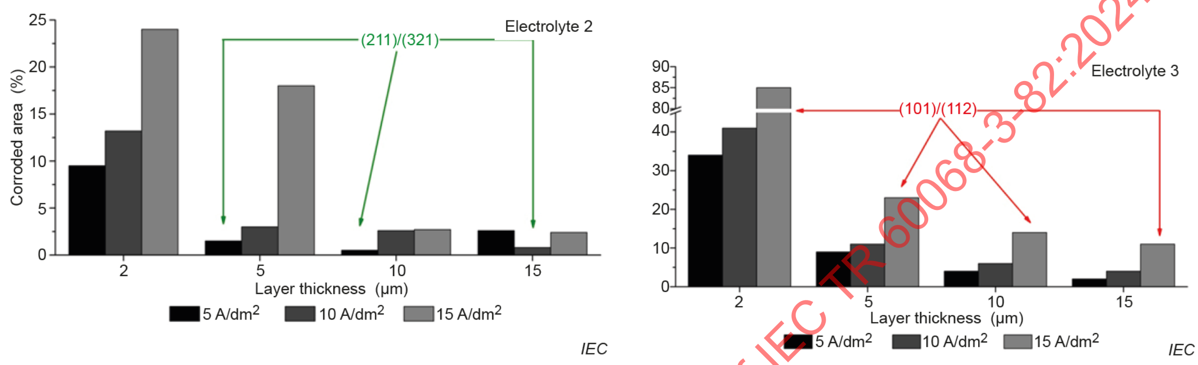


b) **Grain orientation of Sn deposits from electrolyte 3**

Figure 16 – Grain orientation of different Sn surface finishes [32]

All surfaces showed a similar appearance over the complete tested process window. However, it is obvious that the grain orientation can be very sensitive and that even for the same electrolyte, is dependent on the current density as well as plating thickness. In the work from Eckold, only the current density was varied, everything else was kept constant. But it is reasonable to imagine that other parameters would also show a similar impact (e.g.: such as agitation, temperature, concentrations, geometry, plating line set-up, etc.).

The results after the corrosion tests are given in Figure 17 for a) electrolyte 2 and b) electrolyte 3. Green arrows are indicating the resultant preferred grain orientation regarding minimum corresponding corroded area, and the red arrows the non-preferred texture correlating with the increased corroded area.



a) Percentage of corroded area after contamination and damp heat aging for electrolyte 2

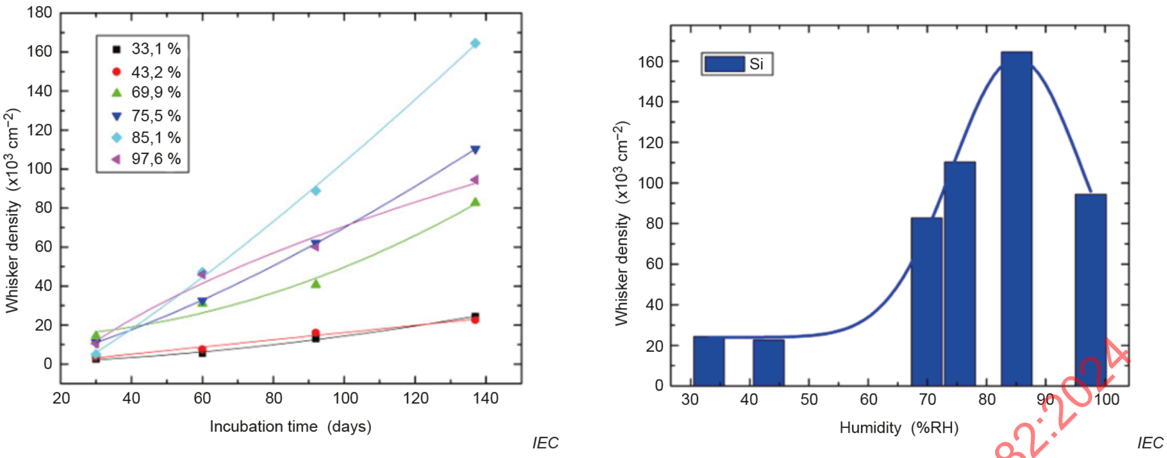
b) Percentage of corroded area after contamination and damp heat aging for electrolyte 3

Figure 17 – Percentage of corroded area after contamination and damp heat aging [32]

Electrolyte 2 had the best performance with minimum whisker growth for the Sn plating with 15 µm and 10 A/dm², while electrolyte 4 showed the best performance with minimal whiskers for the Sn plating with 5 µm and 5 A/dm², both having main orientations in (321) direction followed by the (211). This correlates well with the corrosion results found in Figure 17 where the (211) and (321) orientations show the lowest corrosion propensity and the (101) and (112) have larger corroded regions. It is apparent that the Sn grain orientation plays a role on the corrosion propensity and therefore, related whisker growth. Low indexed grains are showing a higher whiskering tendency, whereas (321) and (211) have an extremely low tendency for whisker growth.

From this work, it is clear that each electrolyte and chosen plating parameters have their own characteristic, like a fingerprint, which are not visible under standard SEM or test methods. This supports the inequation Sn ≠ Sn, which is important to understand for the selection of the right electrolyte for a given plating line. Ideally, it is desirable that the electrolytes are developed and characterized with respect to their ending deposited grain structure, however this is not common practice nor so realistic in mass production industry, which is just another reason why standardized corrosion testing is important and has been endorsed for over a decade.

The classic humidity exposure for whisker tests has come to be well established as 85 % RH. Figure 18 shows Sn whisker results after approximately 140 days at 21 °C in various highly controlled humidity environments ranging from approximately 33 % to 98 % RH using saturated aqueous salt solutions [27]. In order to study the effects of humidity alone and avoid other influencing factors such as chemistry from the electrolyte and IMC formation between film and substrate, thin Sn films (approximately 0,15 µm) were sputter deposited onto Si wafers. It is clear the humidity has a significant impact on the whisker growth with a maximum whisker propensity found at 85 % RH. The experiments were also carried-out on brass (Cu63/Zn36) substrates, where similar results were observed, with maximum whisker densities at 85 % RH.



a) Sn whisker density as a function of time for sputtered Sn on Si at 21 °C with different relative humidity environments

b) whisker density as a function of the relative humidity after ~140 days of exposure

Figure 18 – Whisker density with different humidity [27]

Corrosion tests in the IEC 60068-2-82:2019 can be found in Table 3 using damp heat exposure; 1 000 h at (85±3)°C/(85±5) % RH, for the qualification of new products. Previously (55±3) °C/(85±5) % RH was commonly used with typical exposure times between 2 000 h – 4 000h depending on reference (e.g.: IEC 60068-2-82, JEDEC Standard No.201A [45]). Figure 18 compares whisker results of approximately 8 µm Sn platings on Cu based substrates from multiple different suppliers/plating lines after damp heat exposure at 55 °C/85 % RH. versus 85 °C and 85 % RH, all with a Sn whisker mitigation countermeasure of a post-heat treatment or Ni underlayer.

Table 3 – Overview of Sn whisker results using different testing conditions

	Whiskers > 50 µm		
Plating	**1 000 h 85 °C, 85 % RH**	**4 000 h 55 °C, 85 % RH**	**2 000 h 55 °C, 85 % RH**
1	12	0	0
2	24	0	0
3	29	0	0
4	35	0	0
5	1	0	0
6	0	0	0
7	0	0	0
8	0	0	0

Table 4 – Overview of Sn whisker results using different components

Component type	Whiskers > 50 µm	
	1 000 h 85 °C, 85 % RH	4 000 h 55 °C, 85 % RH
A	3,6	0
A	10,4	0
B	0,3	0
B	1	0
C	0	0
D	0	0
D	0	0
E	0,2	0

NOTE The numbers in the table are the number of whiskers over 50 microns long divided by the number of components investigated.

Whisker testing by 85 °C at a humidity of 85 % RH is undoubtedly superior in order to obtain a clear picture of the whisker propensity for a given Sn finish. Tests conducted with a temperature of 55 °C at a humidity of 85 % RH were not capable of distinguishing a whisker prone plating from a non-whisker prone plating, even when the test duration was 2-4x longer than the test duration of a test conducted with a temperature of 85 °C at a humidity of 85 % RH. The test condition using a temperature of 85 °C at a humidity of 85 % RH. is more sensitive regarding the whiskering propensity of a plating or component and comes with the advantage of shorter testing time. From the results it is evident that platings 1-4 in Table 3 have a higher whiskering tendency compared to 5-8, similar to components A and B in Table 4 compared to C or D.

Another attribute which is known to be able to play a significant role on Sn corrosion is the use of flux for soldering. For further details regarding flux and its influence on Sn corrosion/whisker growth, refer to 4.2.5.3.

4.2.4 Coefficient of Thermal Expansion (CTE) mismatch – Temperature cycling test

The temperature cycling test addresses the risk of whisker growth being generated by the accumulation of internal compression stresses. These originate from mismatches in the coefficient of thermal expansion (CTE) between the base materials and the materials used for plating.

Figure 19 shows the whisker growth during temperature cycling tests due to the differences in base material. Table 5 shows the maximum whisker lengths generated during this test and the differences between the CTE of the base material and the CTE of Sn (ΔCTE). The test conditions are 300 temperature cycles of −40 to 85 °C, with a dwell time of 10 minutes.

These results indicate that increased whisker growth is experienced when the CTE difference between the base material and the Sn plating is higher. These results justify the allowance in IEC 60068-2-82:2019, 3.3 and Figure 2 (Selection of test method), for temperature cycle testing to be exempted when the ΔCTE is less than 8×10^{-6}/K.

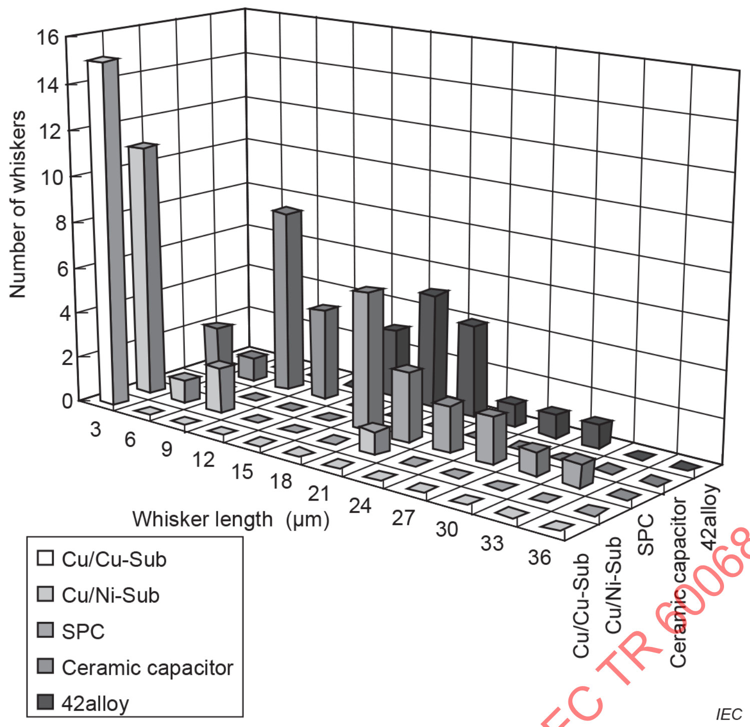


Figure 19 – Frequency and length of whiskers after a thermal cycling test

Table 5 – Relationship between base material CTE, ΔCTE to Sn and the maximum whisker length after thermal cycle testing

Base material	**CTE of base material** $(10^{-6}/K)$	**ΔCTE to Sn** $(10^{-6}/K)$	**Maximum of whisker length after 300 cycles, −40 °C to 85 °C, 10 min dwells** (microns)	
Sn	26,9			
Cu	16,8	10,1	Cu/Cu under layer	0
			Cu/Ni under layer	18,75
Ni	13	13,9		
Ceramic capacitor	10（9～11）	16,9	Ceramic capacitor	12
SPC	10,8	16,1	SPC	32,5
42 alloy	5	21,9	42 alloy	30

Different test conditions were compared to show that the failure mechanisms during ambient ageing and thermal cycling tests are different. Figure 19 shows the results of a thermal cycling test on various base material samples.

Whiskers grew on Sn platings on copper substrates with a copper underlayer when stored at 30 °C and 85 % RH. On the other hand, no whiskers were observed at 30 °C and 85 % RH storage for Cu substrates with a Ni underlayer.

For the ceramic-based components, whiskers grow after a heat cycle. This is due to the higher Delta CTE for the Sn plating on ceramic base materials than for Sn plating on Cu base materials.

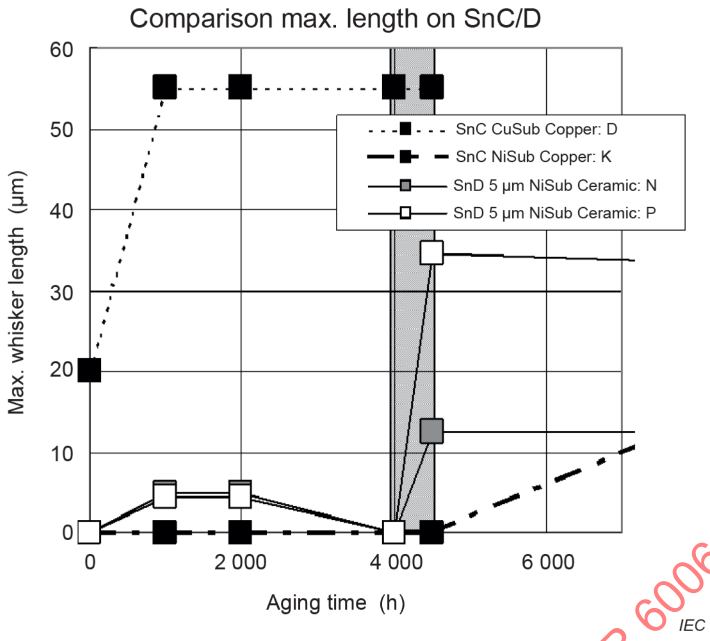


Figure 20 – Comparison max. whisker length with several base materials and combining environment [25]

Figure 20 and Figure 21 show a comparison of whisker lengths generated in an ambient experiment and in a study (fundamental) combining environmental stresses. The sample used was a copper base material plated with 10 µm of Sn sulfate plating. In the fundamental study, to mimic the use of electronic devices in the field, the test specimens were subjected to isothermal ageing at 30 °C 85 % RH (4 000 h), followed by thermal cycling of 500 cycles of −40 °C to 85 °C with 30 min dwells, then ambient and vacuum ageing, followed by thermal cycling of 2 000 cycles of −40 °C to 85 °C with 10 min dwells. In the fundamental study whisker growth was only observed during the stress of thermal cycling. This indicates that under mixed environmental conditions, whisker growth is mainly dependent on thermal cycling. Therefore, it is important to consider the use environment when considering how accelerated whisker testing is undertaken.

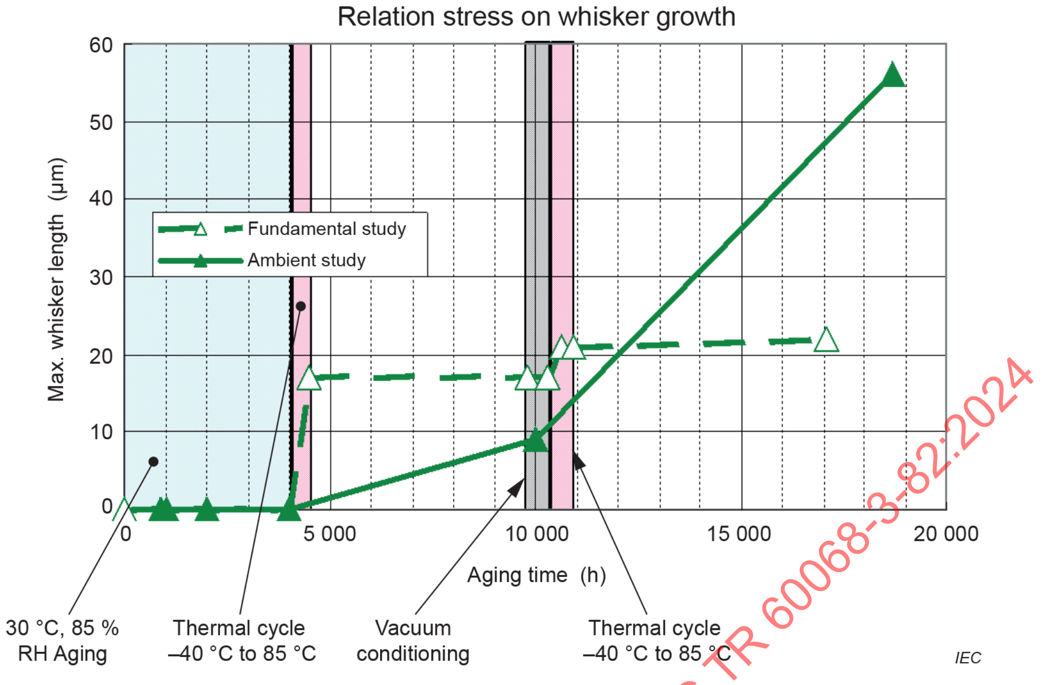


Figure 21 – Comparison of whisker growth in an ambient experiment and a basic experiment combining environmental stresses [25]

To determine acceleration factors associated with thermal cycling, a comparative experiment was carried out using the following temperature ranges:

- from 20 °C to 85 °C (Δ65 °C);
- from –10 °C to 85 °C (Δ95 °C);
- from –40 °C to 85 °C (Δ125 °C).

Methane sulfonic acid (MSA) bath Sn plating on Alloy42 substrates were used for investigation as this combination exhibited a large CTE mismatch between the plating and the substrate.

The distribution of whisker growth on FeNi (Alloy42) base material at 300 cycles is shown in Figure 22.

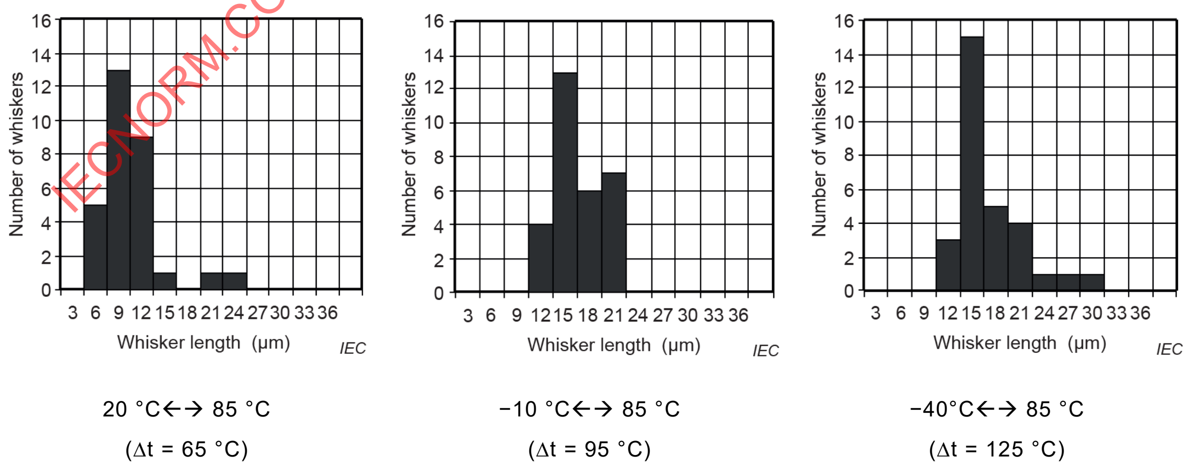


Figure 22 – Distribution of whisker length grown on FeNi (Alloy42) base material after 300 cycles

Figure 23 shows the average whisker length over a longer timeframe for the three thermal cycles (20 °C to 85 °C (Δ65 °C), –10 °C to 85 °C (Δ95 °C) and –40 °C to 85 °C (Δ125 °C)).

Figure 24 shows an example of the relationship between the number of cycles for whisker growth to reach a certain whisker length and each condition from estimates.

As a result, the acceleration coefficient of this test on Alloy42 is explained as follows:

$$\ln(n) = -2{,}8 \cdot \ln\left(\frac{\Delta\vartheta}{1\,\mathrm{K}}\right) + 22{,}2$$

where

n is the number of cycles;

$\Delta\vartheta$ is the range between lower and upper temperature.

In this case, the expansion coefficient of base material influences the acceleration coefficient of whisker growth.

The selection of an acceleration coefficient for this test method is based on Alloy42, the termination material with the lowest CTE.

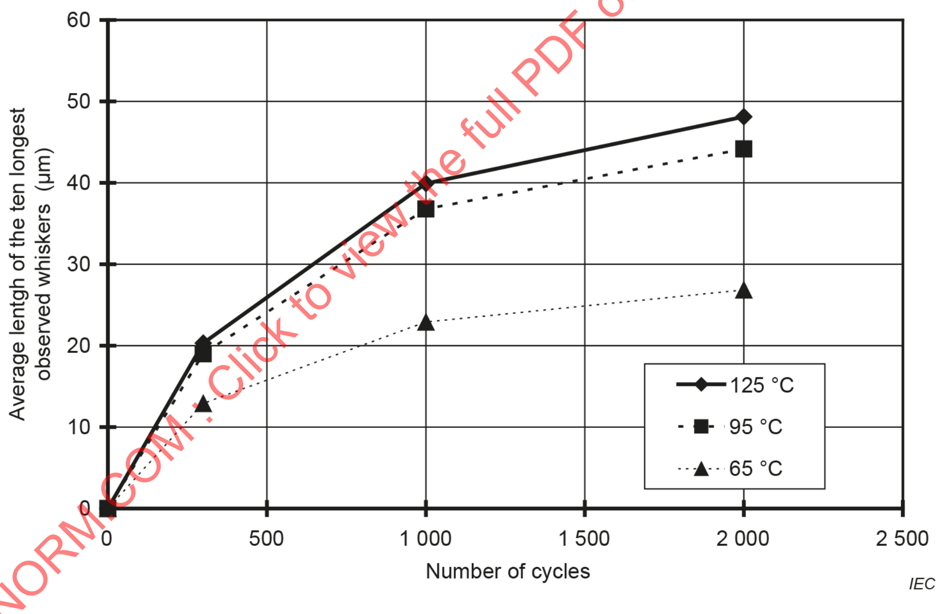


Figure 23 – Whisker growth on FeNi (Alloy42) base material for thermal cycling with Δt of 65 °C, 95 °C and 125 °C

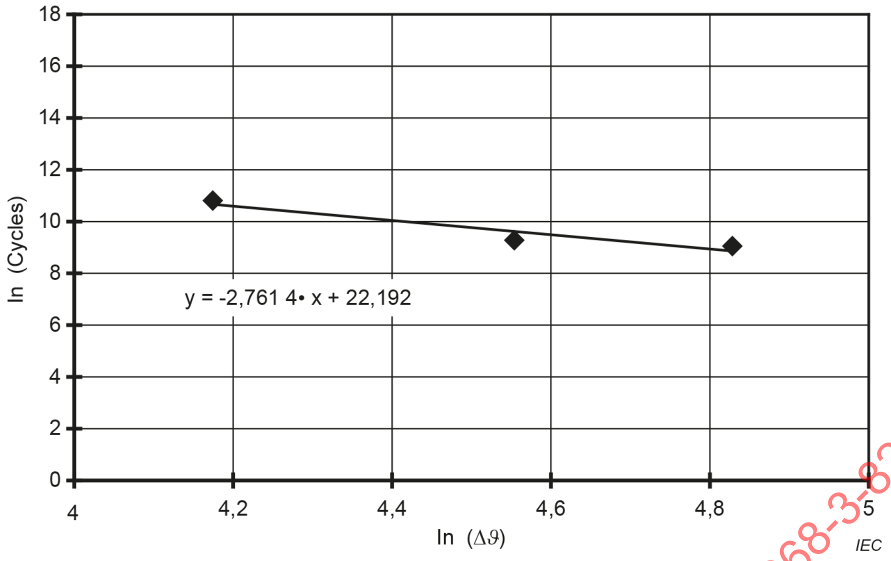


Figure 24 – A relationship of Δϑ and number of cycles for whisker growth on FeNi (Alloy 42) base material to reach 100 µm

4.2.5 Influential process factors

4.2.5.1 General

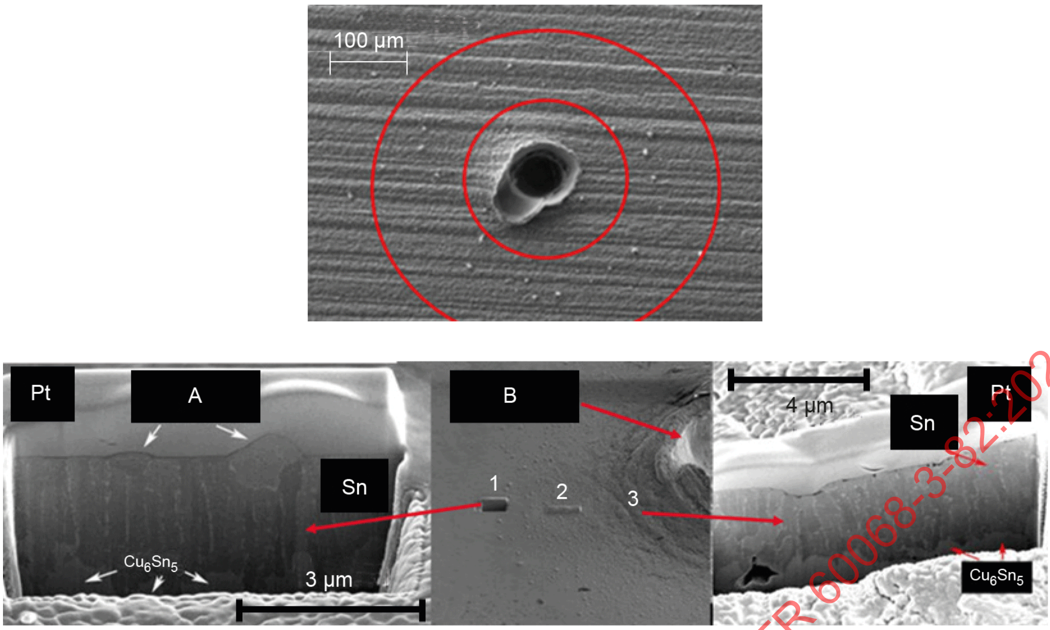
This subclause discusses various production/assembly processes and their effect on whisker growth.

4.2.5.2 External mechanical forces

4.2.5.2.1 General

The use of external forces is in many cases unavoidable (e.g.: bending of leads, mounting of heatsinks and other mechanical parts, press-fit connections, etc.). Nevertheless, when it comes to whisker growth, it is important to distinguish between the different types. Some are critical, some are not, and some are depending on the situation. Confusion is often existing because external forces are associated with stress, which in turn is related to whisker growth. However, to generate whisker growth, sufficient stress in the Sn layer, typically close to the yield limit, with the corresponding stress gradients ($\gtrsim$ 50 MPa/µm [12]), is required. This means, that plastic deformation of the Sn alone does not grow whiskers.

For example, Figure 25 shows an imprint in a Sn film due to the external mechanical force applied on the surface by a test needle, along with FIB cuts carried-out directly in the plastically deformed region compared to its neighboring area [33]. It only took a few seconds to create the imprint, which then resulted in the onset of whisker growth in the areas around the indention, but not directly in the plastically deformed region "3". The plastic deformation itself is actually a stress reduction for the Sn. However, the compressive stress gradients produced in the surrounding region, generate new grains (nucleation sites), as seen in the FIB-cut taken in region "1", and material transport for whisker eruptions.



Key

A newly formed grains

B imprint

Pt Pt layer (protection during FIB cutting)

Figure 25 – FIB and SEM images of the imprint in the Sn film due to a probe needle [33]

The external force which caused in the imprint was only applied on the Sn plating for a few seconds, resulting in short whiskers with a length of approximately 10 µm. This situation dramatically changes if the externally applied forced remains for longer time periods, as can be the case for overmolded Sn plated connectors depicted in Figure 26 [24]. The continuous compressive stress on the Sn plating due to the shrinkage of the plastic molding creates high compressive stress gradients in the free Sn area, where whiskers can grow out. Over time, after the stress gradients are reduced, the whisker growth will stop.

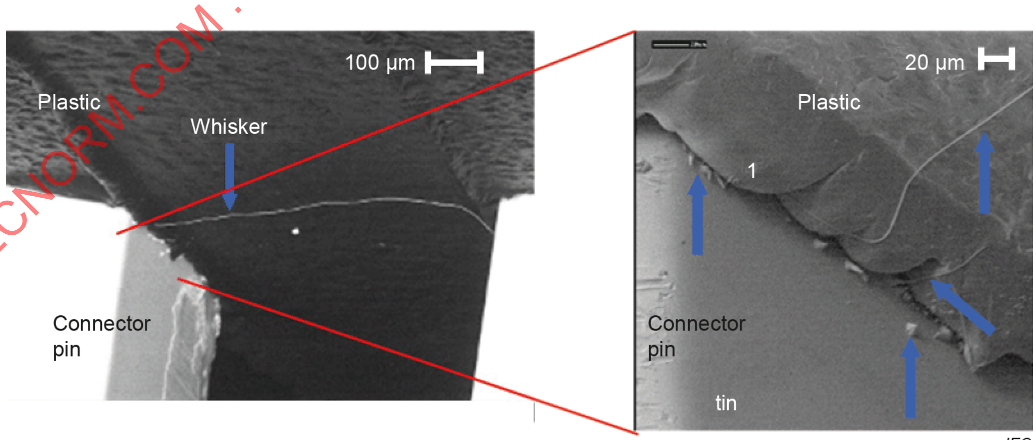


Figure 26 – Whisker growing between to connector pins as a result of the externally applied stressed from the plastic overmold [24]

An overview of further various processes where an external mechanical force is applied on the Sn deposit along with their general impact on whisker growth is provided in Table 6.

Table 6 – Overview of situations where an external mechanical force is applied to the Sn surface finish and their impact on whisker growth

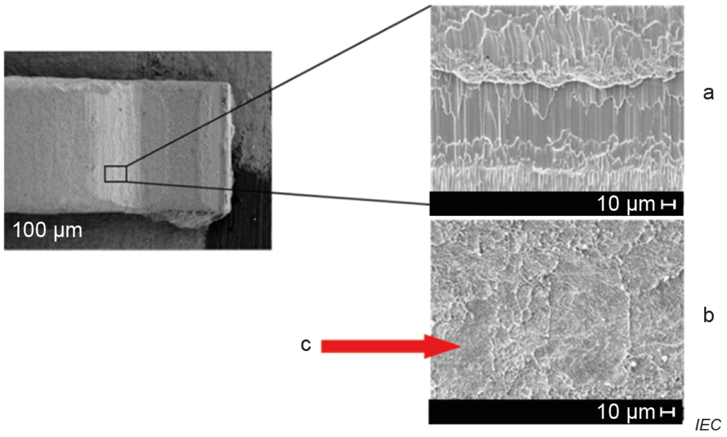
Situation / process	Example / Description	Critical point	Impact on whiskering propensity
Trim and Form (T&F)	Singulation and punching of a pin after plating	Open Cu can lead to a local electrochemical element and enhance corrosion	middle (Corrosion)
Clamping, press-fit, IDC	Continuous pressure on the Sn layer by another component	Small grain size is more critical (promotes diffusion), coating thickness	high
Bending	Bending of a pin with certain curvature	It is possible that cracks in the whisker-mitigating layer occur. In such cases, cracks can eventually be filled with Sn ➔ See 'Brushing'.	Low
Grinding	To achieve a smooth surface, especially for wires after galvanic plating	Original grains are enlarged due to plastic deformation during grinding (> 30 µm) ➔ whisker mitigation	low
Brushing	- After plating without post-processing - After forming plated terminals	Cross contamination Cracked IMC / Ni can lead to direct contact between Sn + Cu ➔ IMC stress	middle high

For one-time processes like bending or grinding, no whisker risk generally is induced. However, if cracks in the whisker mitigating barrier layer between Sn and Cu (e.g.: Ni or purposely formed IMC) occur and then are filled with Sn, resulting in direct contact between Sn and Cu based substrate, then RT IMC growth can lead to whisker formation (4.2.2). On the other hand, situations where pressure is constantly applied on the Sn surface, whisker growth has to be expected. For a deeper understanding of the impact factor on whisker growth due to different mechanic forces, a low risk and higher risk process will be discussed in further detail: bending due to the often misconception regarding whisker risk and press-fit due the unavoidable risk in such a connection.

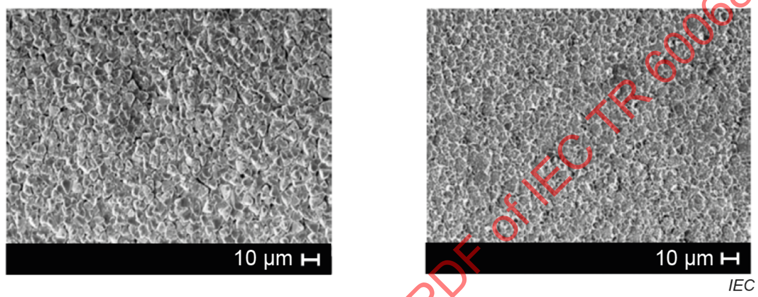
4.2.5.2.2 Bending process

Bending is a typical external mechanical stress process for pins in electronic components or electromechanical connectors, which is often associated with whisker growth. This is a common misconception.

Figure 27 a) presents a pin, which has been bended during trim and form [23]. It is frequently assumed that at the location of the deformation a high whisker propensity will exist. However, no whiskers are observed in this area. This can be better understood when considering the grain size / boundaries of the Sn after deformation. For this purpose, the Sn was etched away, revealing the underlying RT (grain boundary) IMC formation and grain size. The actual grains after forming are approximately 30 µm in diameter, as seen on the lower right in Figure 27 a), compared to the typical diameter of 3 µm to 5 µm for galvanic matt Sn platings without external mechanical stress, shown in b). Consequently, the amount of IMC growth is reduced by a factor of approximately 100. Less irregular IMC growth means lower compressive stress gradients and as a result, no whisker growth is observed.



a) Typical pin after bending during T&F with higher magnification of the deformed Sn plating before and after etching the Sn layer away, revealing the underlying IMC formation



b) Normal Sn deposit, without any external mechanical stress, before and after etching

Key

[a] surface before etching

[b] surface after etching

[c] IMC after trim & form,exhibiting similarity with IMC after post bake, large grains ~ 30 µm

Figure 27 – Sn plating surfaces and IMC structures after bending by Trim and Form and without bending [23]

For another perspective, consider a pin which is plated on all sides with Sn. The typical thickness of a pin, dp, is usually in the range of approximately 1 mm with a Sn plating thickness, dSn, in the range of approximately 3 µm. When bending the pin to a radius R, the concave side will be compressed, whereas the convex side will be stretched. The stress of the Sn layer on the concave side can be calculated according to Stoney's equation. To reach the yield limit of Sn, a bending radius of 2 000 mm would be required. If the bending radius is smaller, plastic deformation will take place, reducing the stress. In real applications, the bending radius is in the range of approximately 5 mm, meaning plastic deformation of the concave side of the pin. The whisker driving force comes, however, from the stress gradients, which for such a Sn layer is < 0,02 MPa/µm. This is more than a factor of 2 500 below the characteristic threshold for whisker growth.

Therefore, Sn whisker growth is not related to the bending process of the pin by itself [4]. In the cases where whisker growth is observed in the bending area, the reason for the whisker growth is due to other underlying effects. A primary example is damage, in the form of cracking, of the whisker mitigating barrier layer (e.g.: Ni or IMC) between Sn and Cu. If this occurs, Sn can obtain direct contact with the Cu based alloy material, meaning whisker growth is not only likely, but can lead to whisker lengths up to a few mm long.

Hence, it is important to assess all manufacturing and subsequent handling process steps to ensure that any whisker mitigating countermeasures are not destroyed.

4.2.5.2.3 Press fit technology

In compliant press-fit connections, a pin is pressed into a plated through hole (PTH) smaller in diameter than the pin depicted in Figure 28. This means that any standard intrinsic stresses inherent in a Sn film are now coupled also with permanent external stress, which generates extreme stress gradients within the Sn film. Depending on pin size, geometry and base material properties (e.g. elasticity) as well as the PCB layout and PTH diameter, the compliant radial forces can easily vary to well over 100 N. Consequently, the unique and advantageous characteristics of press-pin, consisting of just a one-step press-in process, creating both the essential electrical and mechanical properties, will always come with the unavoidable challenge of whisker growth.

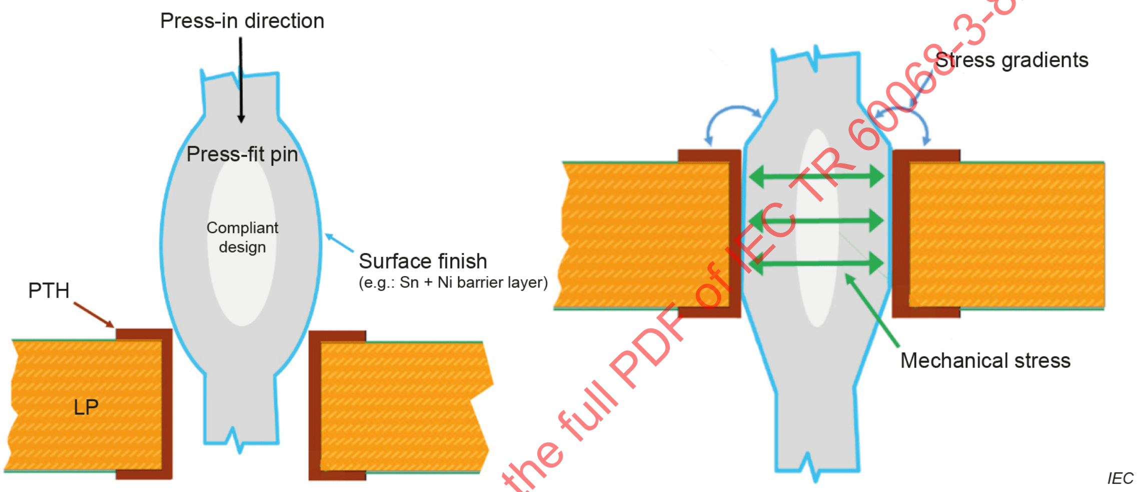
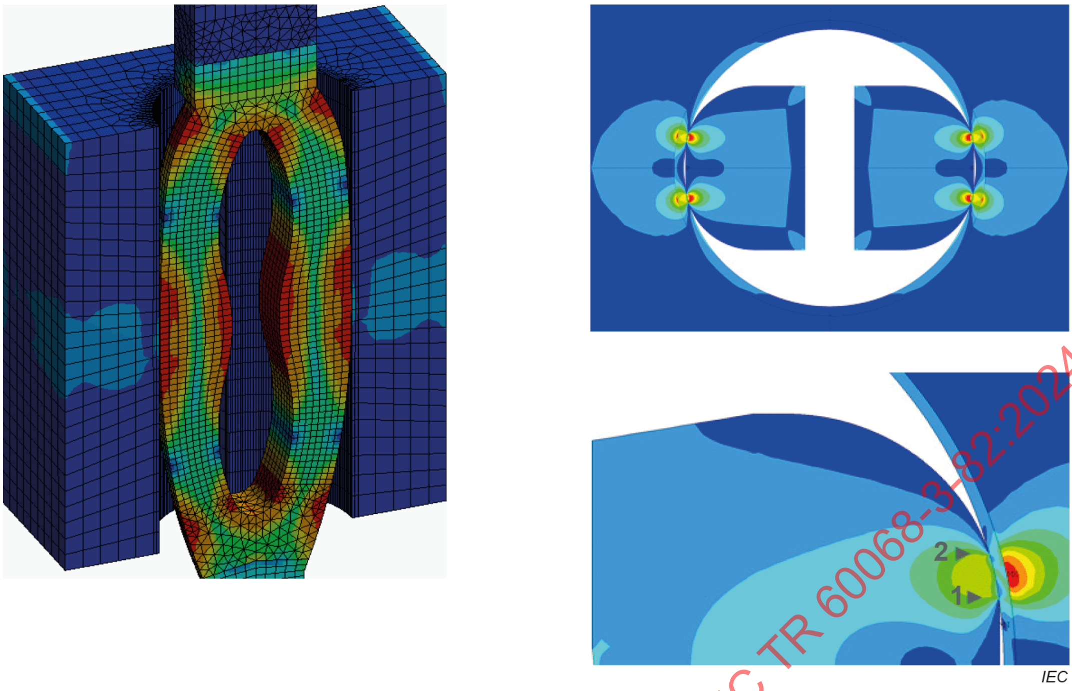


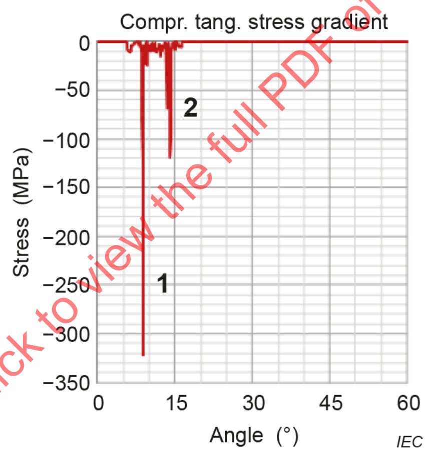
Figure 28 – Schematic representation of a press-fit connection [35]

As the high normal forces and resultant stress gradients after mating are the dominating influential factors generating whisker growth in press-fit connections, it is logical that the whisker test prescribed in the IEC 60068-2-82:2019, 6.5 (or IPC-9797 [37]) is simply carried-out on pressed-in pins at RT conditions. Due to the immediate continual large external mechanical stress, whisker growth is promptly initiated after press-in and therefore, a total test duration of 2 000 h is sufficient to assess the whiskering propensity of the contact.

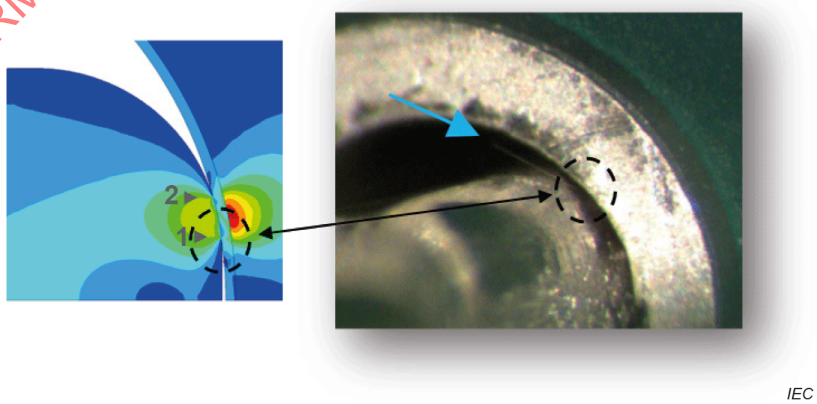
A simulation of the stress distribution and corresponding stress gradients in a press-fit zone is given in Figure 29 a) and b) respectively along with an example of Sn whisker growth directly out of a high stress gradient region between pin/PTH in c) [34]. In the simulation, compressive stress gradients as high as > 300 MPa/degree were found, demonstrating the initial condition of a press-fit connection after insertion and why whisker growth is to be expected. Through such simulations, the corresponding stress regions and gradients in different press-fit zones / PTH connections can be compared and pin properties accordingly optimized as a countermeasure against whisker growth.



a) **Simulation of stress distribution in a press-fit zone**



b) **Corresponding stress gradients**



c) **An example of Sn whisker growth from a press-fit zone**

Figure 29 – A simulation of the stress distribution and corresponding stress gradients in a press-fit zone [34]

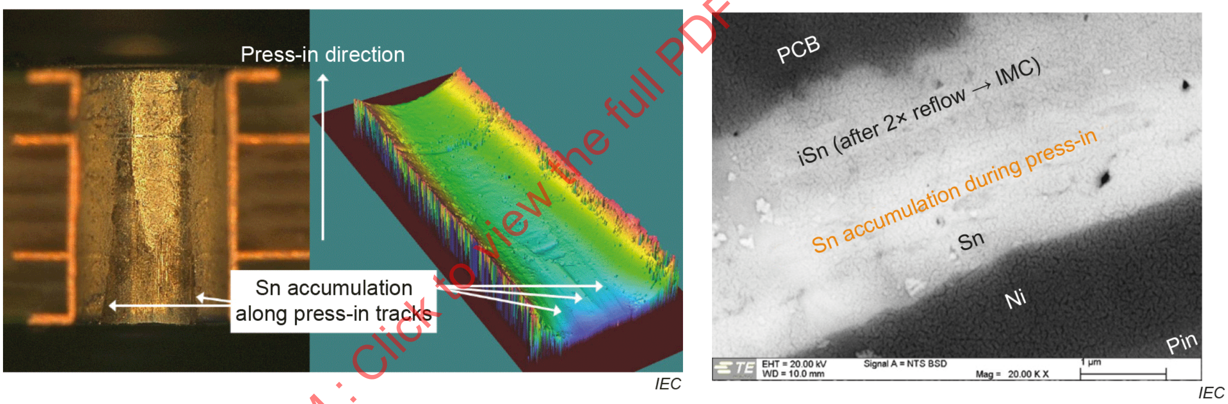
The other principle whisker countermeasure for press-fit lies on the pin's finish.

Due to the roles a surface finish plays in the reliability of a press-fit connection, the importance of one is clear:

- reduction of friction for the press-in process results in reduced insertion forces and PCB deformation;
- oxidation/corrosion protection for substrate material;
- desired cold welding connection for high reliably press-fit connections.

Though the surface finish provides the source for whiskering material, the pin's layer system can also be modified to help reduce the growth of long, high-aspect ratio Sn whiskers, further than just a Ni barrier layer.

During press-in the pin's surface finish is smeared, with some of the material being scrapped-off and relocated, typically accumulating along the periphery of pin/PTH interface as well as in regions near the press-in side (Figure 30 a)) as a result of the directional friction forces working against the press-in movement. Granted the smearing and plastic deformation of the finish is important for the contact physics mechanisms in the pin / PTH interface, it also creates an excess of Sn whiskering material, that is directly squeezed between the pin/PTH in high stress gradient regions, as shown in Figure 30 b). This explains why the majority of protruding whiskers are usually observed growing in the PTH or from the mating side of the press-fit contact compared to out the pin's tip side (as seen in Figure 29).



a) Contact grooves in the PCB hole from pressing-in with the corresponding accumulation of Sn

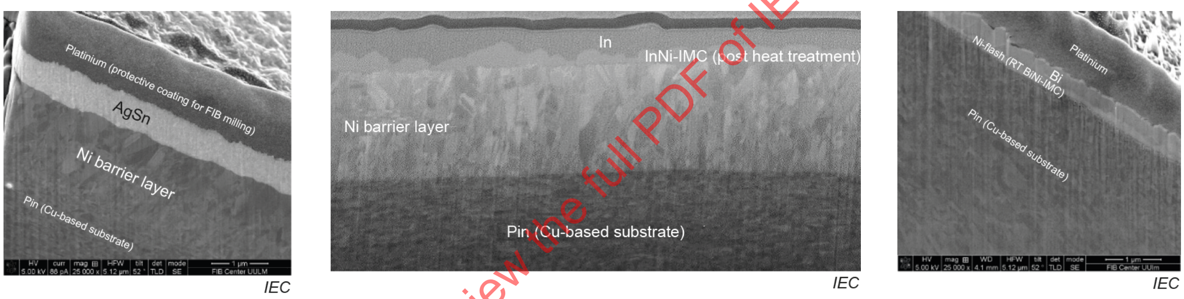
b) a cross-section of a Sn plated pin with Ni underlayer pressed into an iSn PCB, demonstrating accumulation of Sn between plated pin / PTH interface

Figure 30 – Contact grooves in the PCB hole from press-in operation and cross-section of a Sn plated pin with Ni underlayer [35]

To reduce this effect, a thinner Sn finish is useful to minimize the build-up of Sn directly in highly stressed locations. This exception is unique to press-fit, since typically a thicker Sn film is generally used against whisker growth in other applications where such effects do not occur, as previously discussed.

Further surface finish modifications include the use of a Sn-alloy deposit instead of pure Sn. Here is an exception where SnPb is currently still sometimes used, however, due to the progression of continually stricter regulations on Pb, this is fading out more and more. The most common alternative Sn-alloy being used instead of SnPb is AgSn, with the incorporation of a Ni barrier layer. The goal here to form a AgSn IMC (mainly Ag_3Sn) so that there is no free Sn left to potentially whisker. This can be accomplished in two ways: depositing a multi-layer system, meaning Sn and Ag separately, followed-up with a post-heat treatment or through the co-deposition of Sn and Ag concurrently from one electrolyte, with favor and common practice lying on the latter method due to simplicity, time and energy.

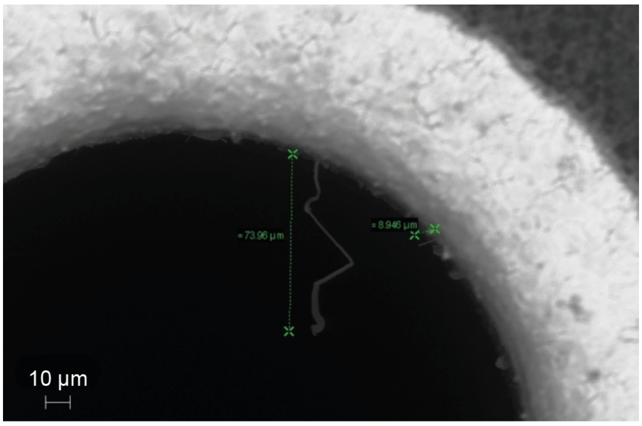
Taking the mitigation strategy even one step further, another option is to remove Sn all together and use a Sn-free surface finish. The current Sn-free solutions include Indium (In), Bismuth (Bi) or a multilayer Ni film system. The greatest advantage with such surface finishes is, of course, the reduced whisker risk, as these materials are not known to acquire the same whiskering tendencies as Sn. However, as with all new product changes, the finishes need to be tested and validated accordingly to their end application requirements (e.g.: press-fit zone and PCB technology, header vs stand-alone pin, service environment in the field), especially whiskering characteristics whenever dealing with press-fit connectors. Even metals, which have never been observed to grow whiskers in the practice, can still whisker under the extraordinary conditions of press-fit. For further information on such film systems, please refer to the available literature (e.g.: [36]) or directly contact the plating suppliers. Figure 31 displays representative FIB-cuts of a AgSn, In and Bi film system.



a) AgSn **b) Indium** **c) Bismuth film systems**

Figure 31 – Focused-ion beam investigations of different surface finishes [36]

Though the primary whisker growth transpires from the mechanically pressed compliant pin's finish, whiskers can also grow from the initial Sn plated Cu vias on immersion Sn (iSn) PCBs due to irregular RT IMC formation especially in combination with the existing stress gradients created after pin insertion. To reduce the whiskering propensity of iSn platings, a small amount of Ag (e.g.: approximately 0,5 % wt to1,5 % wt) is added in the Sn finish, however, as seen in Figure 32, this does not completely prevent Sn whisker growth from occurring, it only helps mitigate.



IEC

Figure 32 – Whisker growth from an iSn with Ag additive (for whisker mitigation) plated via after 1 000 h at 85 °C / 85 % RH aging

The 2x reflow process specified in the IEC 60068-2-82:2019 (5.5.1) before press-in greatly supports in this matter. As with all preconditioning measures in the standard, it is required to best align testing with the custom practice for each application. Since press-fit components (e.g.: header) are normally attached to the PCB after the soldered components, it is typical for the PCB to be exposed to 2x reflow before press-fit pins are inserted. As a result, an IMC barrier layer between the immersion Sn finish and Cu via is developed, hindering further irregular RT IMC growth over time, which in turn reduces the whisker risk. Furthermore, since the iSn film is only approximately 0,5 µm to 1,3 µm thick, it also leaves little remaining free Sn in the PTH for whiskers to from and due to the pinning effect, it mitigates diffusion within the film.

4.2.5.3 Soldering

During soldering there are multiple variables to consider, which could affect whisker growth, including the flux type, solder composition and corresponding required reflow profile. Therefore, appropriate consideration and preconditioning depending on component technology (i.e.: surface-mount or through hole) is required to reliably test the whiskering tendency.

The heat exposure alone during soldering is not increasing the whiskering propensity on the Sn plated terminations, but instead can reduce the whisker probability, as discussed in clause 4.2.2. However, it is often the case that the Sn finish does not fully melt during serial production reflow, as shown in Figure 33. Here there are areas where the original Sn grains are no longer present (i.e.: melted) and areas where the grains are still visible. In the non-melted regions, where the grains are still visible, whisker growth occurs. This is a good example why in Table 1 a) of IEC 60068-2-82:2019, it is required to melt the Sn finish during reflow for an effective whisker mitigation.

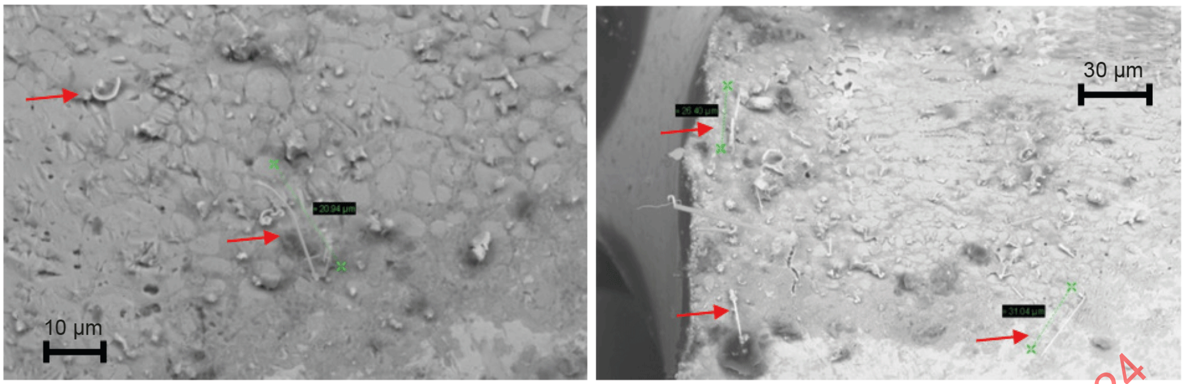


Figure 33 – Pure Sn plated pin after Pb-free reflow process using solder paste under serial production conditions

There is often the misconception that preexisting whiskers, which have grown over time on the shelf, will melt away during reflow assembly. However, this is not necessarily the case. The melting of whiskers has been observed, as shown in Figure 34, but only after 3x reflow at a max. temperature profile (40 s at 260 °C) [23].

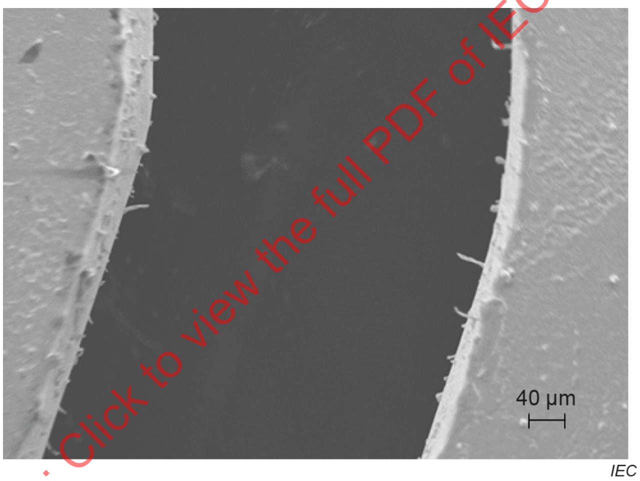


Figure 34 – Sn plating after 3x reflow (40 s at 260 °C) [23]

The soldering alloy, on the other hand, can play a crucial with respect to whisker growth [38], [39]. Rare earth elements especially have been observed to increase the whiskering propensity [40]. This lies mainly on corrosion of the solder due to differences in the electrochemical potential of the rare earth elements and their IMCs.

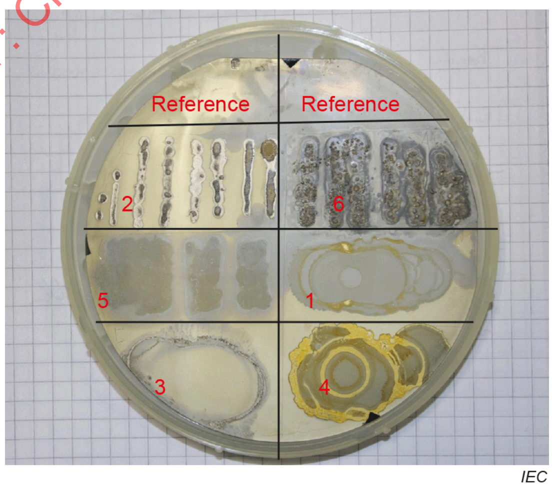
Corrosion characteristic of Pb-free Sn-Ag based alloys has been investigated, including the usage of potentiodynamic polarization curves measurements [41]. Commonly used SAC solders, such as SAC305 (3 % Ag, 0.5 % Cu and remainder Sn) and SAC407 are comparable in respect to whisker growth, with the longest observed whisker at 90 µm after temperature cycling (1 000 TC; −40 °C/85 °C).

Out of all the variables involved in the soldering process, flux is known to be the most relevant factor for whisker growth, due to the impact their residues have on corrosion induced whiskering on the Sn finish of the component. For this reason, several different flux systems were tested in order to assess their influence on whisker growth [43]. The investigations were carried-out in such a way, so that only corrosion induced whisker growth could be considered and all the other influencing whisker mechanisms excluded. Therefore, a 10 cm diameter Si-wafer was used with a sputtered 20 nm adhesion layer of Ti, followed by a 20 nm Ni layer, which then has no negative impact on the expected whisker growth. Finally, a 5 µm matte Sn finish was galvanically deposited using a classic MSA based electrolyte and rinsed with DI water, in correspondence to a standard serial production plating. The exact electrolyte and plating parameters for this study were specifically chosen based on previous tests, which showed an inherent whiskering propensity under the existence of compressive stress gradients induced by the corrosion of Sn. The different fluxes where then dispensed on the Sn finish in separate regions of the wafer using a 250 µm tip needle, followed-up by reflowing the entire Si wafer. Paste flux was applied in rows and liquid flux as drops on the surface, comparable to a typical SMD process. The various tested fluxed are summarized in Table 7.

Table 7 – Overview of the tested fluxes for their impact on the whisker growth

Name of flux	Flux type	Whisker > 100 µm	Remark
1	ROL1	4	High activated, clean
2	ROL0	68	No clean
3	ROL0	48	No clean
4	ROL0	63	No clean
5	ROL0	26	No clean
6	ROL1	4	High activated, clean
7	No flux	4	Cross contamination

The wafer was then exposed to damp heat cycling: 85 °C / 85 % RH for 1 000 h. The resulting appearance of the surface after aging due to the different fluxes is given in Figure 35. It is obvious the behavior of the individual flux systems differ and therefore, also the corrosion induced whiskering propensity.



NOTE A cross contamination by other fluxes could not be 100 % excluded [43].

Figure 35 – Appearance of the Sn surface due to the various flux systems and their corresponding residues after reflow (min. Profile) and 85 °C/85 % RH exposure

A detailed investigation of the whisker growth was performed using a scanning electron microscope, as depicted in Figure 36. In total, whisker growth from an area of 875 mm^2 was documented in order to create a statistical data set for the assessment. Figure 37 summarizes the observed whisker growth for a ROL0, ROL1 and no flux sample as reference (numbers 4, 1 and 7 respectively from Table 7).

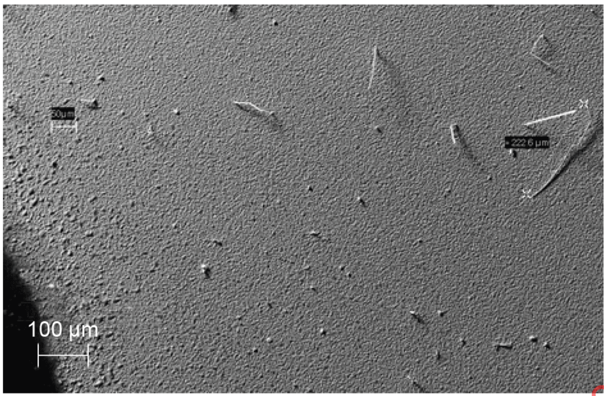
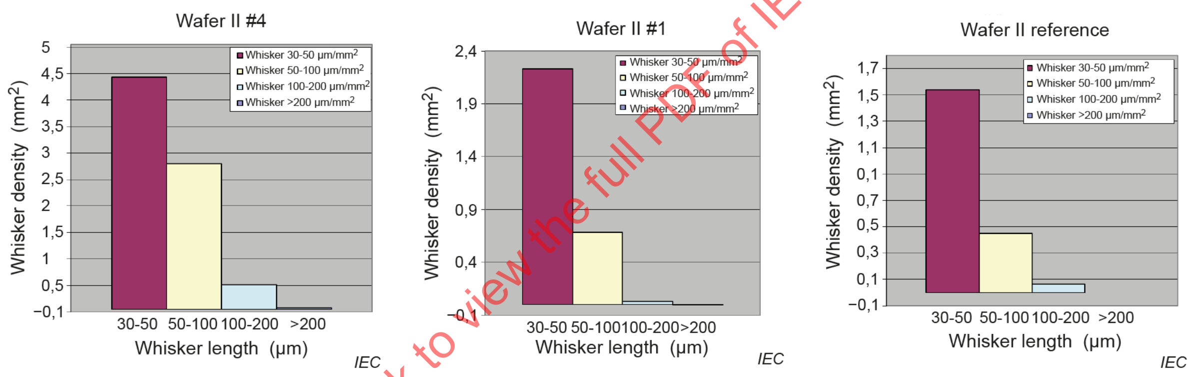


Figure 36 – Representative whisker growth near areas where flux residue is located



a) **ROL0** b) **ROL1 (higher activated flux)** c) **no flux as reference**

Figure 37 – Whisker density with no flux and several flux types

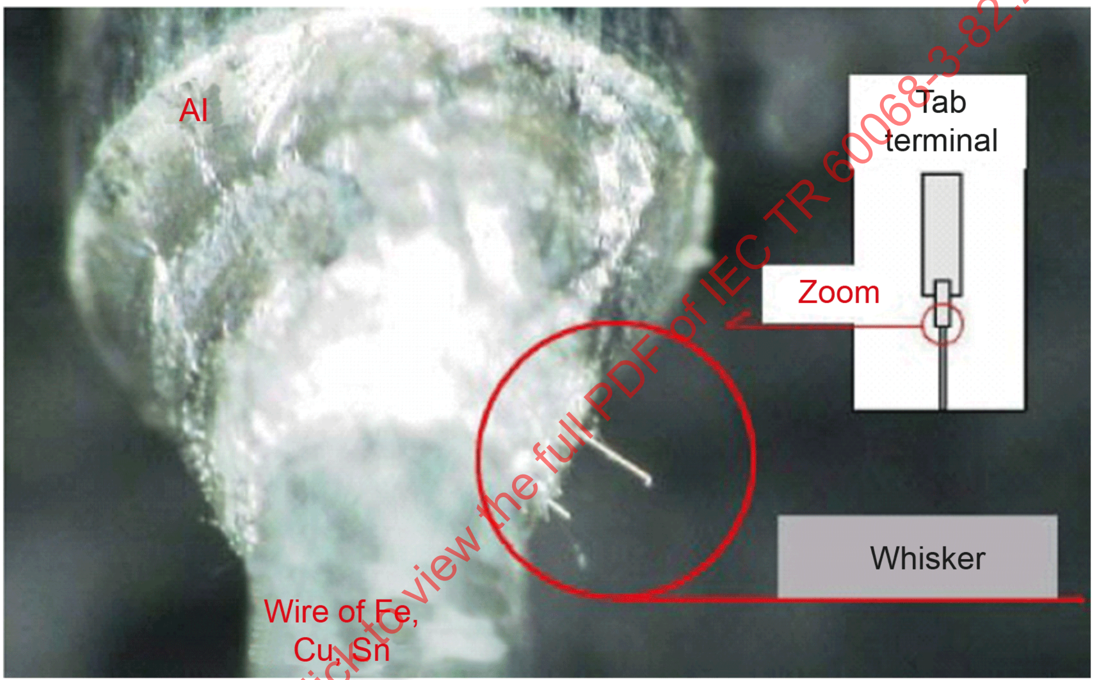
Most of the whisker growth was observed near the areas where residue and resulting corrosion products after aging where located on the surface, as seen in Figure 36, with some whiskers growing directly in the residue regions as well. The higher activated, ROL1, flux is showing slightly higher whisker densities compared to the reference, no flux, sample for whiskers < 100 µm long. However, for whisker growth > 100 µm, the samples show similar whiskering tendencies, where only 4 whiskers were observed for both, as given in Table 7. Whereas the corrosion induced whisker growth from the standard, ROL0, flux is a factor of 3x higher compared to the higher activated flux, with 63 whiskers observed < 100 µm. Due to impact flux has on corrosion induced whiskering, the preconditioning required in Table 2 of the IEC 60068-2-82:2019, using a standard ROL0 flux system, is critical to assess the whisker risk in the different assembly processes for surface mount and through-hole soldered components.

4.2.5.4 Welding

For the lead wire that is the external terminal of the Al electrolytic capacitor, a part made by butt-welding a Sn plated steel wire (hereinafter CP wire) and an Al wire (hereinafter tab) is used. Sn whiskers may occur in this area.

Whisker growth and welding are not directly correlated. The welding of Sn plated Cu-alloys is not causing a whisker growth, since the Cu and Sn are forming an IMC, the remaining Sn is not forming whisker afterwards. The same is valid for welding of Fe alloy. The Fe or Cu material can form intermetallic compound with the other materials during the welding process. The solidification takes place in a certain sequence following the melting temperature. First Fe, Cu, Al and Sn.

This situation changes if one of the welding counterparts is out of an Al-alloy in combination with the presence of Sn. During the welding process the base material is heating up until the melting point is reached, in order to create a form-closed durable connection. The Sn whiskers in this weld are grown when the Sn phase becomes a three-dimensional network structure in the alloy region of Al-Sn, and it is considered that the residual stress inside the weld is the driving force for growth (see Figure 38).

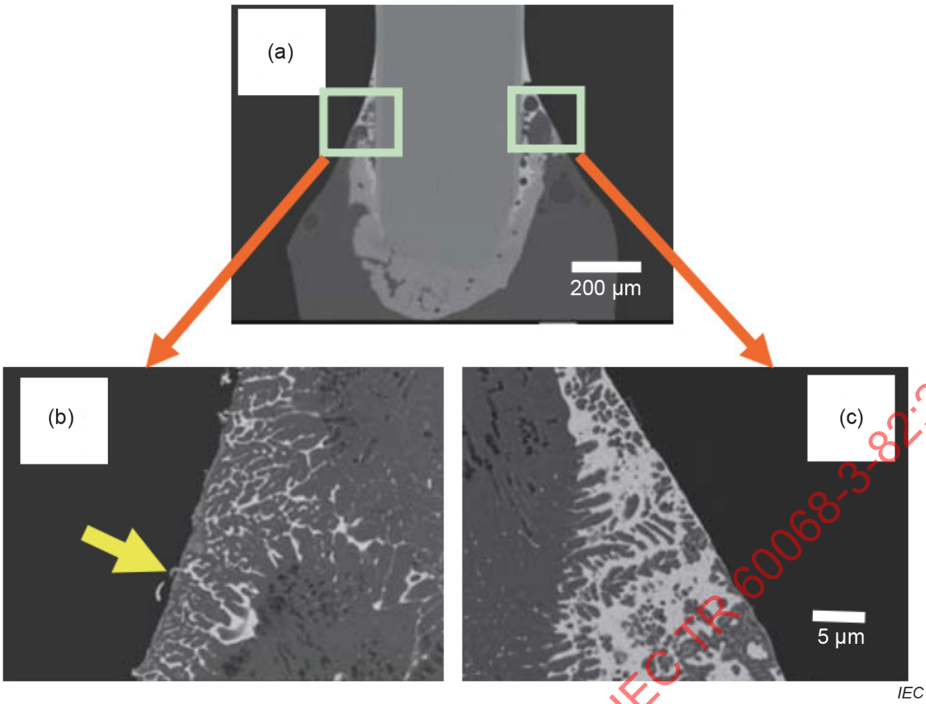


The whisker has a length of approximately 150 µm.

Figure 38 – Sn whisker growth at the area with Al welding point

The solid Al is causing a compressive stress due to the shrinkage on the entrapped Sn. This situation is similar to that of a tube of toothpaste. The compressive stress will create very fast (in several weeks) very long whisker, up to several mm long. Whisker growth is initiated directly after the completion of the welding process and is typically completed within a time period of a few weeks, depending on microstructure and local Sn distribution in the welding joint (see Figure 39 [42]). Considering the local microstructure, comprising the Sn coated wire and the intermixing of Al with Sn, Figure 2 in IEC 60068-2-82: 2019 applies. This results in the following applicable tests: Damp heat, temperature cycling as well as the ambient test.

As a method of mitigating these Sn whiskers, it has been confirmed that Sn whiskers are grown when the solidification conditions are water-cooled, but not when the furnace is cooled. From this, it is known that slowing down the cooling rate at the time of solidification and forming Sn as a large colony has an effect of mitigations Sn whiskers.



Reproduced from [42] with permission.

Figure 39 – Feature of formation area of Sn whisker welding point

5 Whisker testing

5.1 Preconditioning

5.1.1 Pre-aging before testing

The mandated pre-ageing assures that all specimens are brought to a comparable level prior to whisker testing. Pre-ageing at room temperature and humidity is particularly crucial for terminations in which copper diffusion processes can occur. Typically, this is relevant for Cu lead frames where no Ni barrier is present or no post-deposition treatment (e.g. annealing) has been performed. During storage, intermetallic growth is initiated because of copper diffusion into the Sn layer. As discussed in Clause 4, this will lead to the build-up of compressive stresses within the Sn plating and, eventually, the onset of whisker growth. The intention of pre-aging is not to force whisker growth but to replicate the normal process of handling and manufacturing of terminations and allow for associated microstructural changes which may occur, particularly for systems lacking effective whisker mitigation. A typical storage time in the supply chain prior use of components is 30 to 120 days. A suitable pre-aging time in the above-mentioned range needs to be chosen, representative of the components expected time from plating to processing. A standard laboratory environment of (25 ± 10) °C and a (50 ± 25) % RH is sufficient for pre-ageing and thus a dedicated temperature chamber is not necessary. Accelerating pre-ageing is not desirable as acceleration factors for this environmental condition are unknown.

5.1.2 Preconditioning of test specimen intended for press-fit applications

During and after press fit processing, mechanical stresses can affect the Sn layer and cause internal stresses. This is largely independent from the base material or underlayer platings. To simulate this stress, the samples need to be inserted into a standard printed board. Care needs to be taken to choose the appropriate hole size, similar to that used for the termination during manufacturing. Small differences in the hole size can have a large impact on the stress levels in the Sn layer. To eliminate internal stress in the test circuit board, that otherwise can affect the test results, a heat treatment of the board before the press-in operation is essential. A common pre-heat treatment for printed boards is a reflow process, which needs to be applied twice, to replicate a typical process flow consisting of double-sided reflow followed by the press-in operation. See 4.2.5.2.3 for more information.

5.1.3 Preconditioning of test specimen intended for mechanical loads other than press fit

During manufacturing or further processing, terminations can be subjected to mechanical processes (like bending, stamping etc.) that can either affect internal stresses in the Sn layer (which normally has no effect to whisker growth, see 4.2.5.2 and 4.2.5.2.2) or negatively impact whisker mitigation measures (e.g. by cracking of Ni underlayers or otherwise creating direct contact of the Sn finish layer with the base material, thereby 'bypassing' a Cu diffusion barrier), more explanations see 4.2.5.2.2. To simulate this stress, samples need to be subjected to the expected stresses that occur during processing. Because of the large variety of processing conditions and sample geometries, a standardisation of this test is not possible. It is therefore the responsibility of the supplier to select appropriate load conditions to simulate the expected processing conditions. An overview of typical process situations and their whisker risk gives Table 6 in 4.2.5.2.

5.1.4 Preconditioning of test specimen intended for soldering / welding

As mentioned in 5.1.3, it is clear that any mechanical loads arising during processing have to be taken into account. Parts to be used for testing therefore need to be in the finished state, with all forming operations completed. If the intended mechanical loads in the customer's process are known, these loads need to be applied to the samples. If the customer's process isn't known and a forming operation during assembly is likely, bending of the terminals is an alternative solution. A single bend of 90 °during assembly is usual. Terminations that are not pliable are not subjected to the bending pre-conditioning.

Additionally, soldering or welding results in thermal exposure for the parts. The temperature and exposure time conditions define the thermal energy imparted to the parts. As a result, these thermal exposures affect the growth of IMCs, not only in terms of thickness but also in their composition. As mentioned in 4.2.2., the type of IMC has a large impact on whisker growth. On the other hand, only partly molden surfaces with remaining original Sn grains carry a high whisker risk, as discussed in 4.2.5.3. Hence, for parts intended for reflow processing, a suitable reflow profile within the limits of the test conditions, needs to be carefully selected according to IEC 60068-2-58:2019, test Td1. The standard offers different reflow profiles in terms of peak temperatures and exposure times. For the most cases, a profile from process temperature group 3 (Solder alloy Sn-Ag-Cu) is applicable.

For parts intended for through-hole assembly, dipping to a depth of at least 4 mm, but to a maximum depth of 50 % of the length of the termination in a solder bath is recommended. Temperature and flux per IEC 60068-2-20 is used.

As welding is not a standard process, the relevant specification has to give appropriate information on the thermal excursions likely to be experienced.

As shown in 4.2.5.3, the type of flux applied in the soldering process has a large impact to whisker growth, whereby ROL1 (activated) has not the most effect to whisker growth, comparing to type ROL0 (non-activated). As it is impossible to test with all fluxes available in the marketplace, an ROL0 type flux according IEC 61190-1-1 or ISO 9454-2 in solder paste form or as a flux for dipping is usually used.

5.2 Ambient test

5.2.1 General

The ambient test addresses the diffusion process of copper into the Sn layer during service life. Copper and Sn form an Cu_6Sn_5 intermetallic compound (IMC) that grows in the Sn matrix along the grain boundaries. The mechanism is explained in 4.2.2. As a result, the IMC exerts compressive pressures on the Sn grains and causes whisker growth.

This whisker growth mechanism is relevant for all plating combinations, in which Cu diffusion can occur. For these combinations, the test is mandatory, as stated in Figure 2 of IEC 60068-2-82:2019. Exceptions are described in Table 1, which also gives is a collection of mitigation measures. The intention of these measures is to:

a) inhibit copper diffusion or

b) force the growth of favourable IMC or

c) spread the compressive stress over a thicker Sn layer.

To a): Inhibition of copper diffusion can be achieved by use of a nickel interlayer. Typical layer thicknesses in the range of (2 ± 0,5) µm can reliably restrict Cu diffusion. Thinner Ni layers are possible, if the plating process delivers good plating quality (pore-free layers with an even thickness). Care should be taken with surfaces intended for forming processes. The nickel layer has to be ductile enough to allow these processes to be undertaken without cracks forming in the Ni interlayer.

To b): As mentioned in 4.2.2, heat treatments like solder reflow or annealing, forces the growth of the Cu_3Sn IMC, which forms an even layer between substrate and Sn plating. This layer prevents or decelerates copper diffusion in the Sn grain boundaries, which is the main reason for compressive stresses in the Sn layer. Acceptable and effective heat treatments are reflow or hot-dip plating and for thicker layers, annealing below the melting point of Sn is preferred, see also c).

To c): For thick layers of Sn, there is a greater opportunity to reduce stress in the Sn layer due to the larger volume of tin present. Sn is a ductile and comparative soft material, and therefore there are good chances for stress relaxation to occur. For thicker layers (> = 7 µm), annealing below melting point of Sn is sufficient. Reflow can here result in dewetting.

If one of the exceptions in IEC 60068-2-82: 2019, Table 1 is applicable, the ambient test can be omitted.

5.2.2 Test severity

A standard laboratory environment of (25 ± 10) °C and (50 ± 25) % RH for storage is sufficient as explained in 5.1.1. No acceleration factor known in the range of this condition. Concerning the storage time, it can be assumed that the risk of later whisker growth is low, if no whiskers have been observed after 4 000 h of storage at ambient conditions. As the IMC thickens, whisker growth will normally slow down as Cu diffusion is decelerated due to the extensive IMC growth. This of course depends on Sn-plating thickness and microstructure including plating quality (content of organic contaminants) and also the type of plating.