iNEMI Recommendations on Lead-Free Finishes for Components Used in High-Reliability Products
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I. Executive Summary

The iNEMI Tin Whisker User Group consists of eight large manufacturers of high-reliability electronic assemblies. These companies, which annually purchase many millions of dollars of components, formed the User Group to develop recommendations for lead-free surface finishes for high-reliability electronic applications. These recommendations are intended to minimize the risk of failures from tin whiskers. It is the consensus of the iNEMI User Group that pure tin electroplating presents a risk in high-reliability applications, and that there are cost-effective alternatives available to minimize this risk.

The industry has made significant progress in standardizing its approach to tin whisker mitigation and testing. Three standards/publications were released in 2005 and 2006 addressing tin whisker testing, environmental acceptance requirements and mitigation practices (JEDEC standards JESD22A121.01, Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes, and JESD201, Environmental Acceptance Requirements For Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes; and JEDEC/IPC joint publication JP002, Current Tin Whiskers Theory and Mitigation Practices Guideline). The User Group strongly supports and endorses the use of these documents as part of a comprehensive strategy of mitigation practices, tin whisker testing, and plating process controls necessary to reduce the risk of failures associated with tin whiskers.

This document updates the report originally published by the group in June of 2003 and last updated in May 2005. It presents recommendations for component finishes for a variety of applications and reflects the best judgment of the iNEMI User Group members, based on their own experiences and the available data. Twenty seven general guidelines for migrating to Pb-free component finishes have been used in developing these recommendations. This document is not intended to address mission critical applications such as aerospace. These guidelines are generally inadequate for those types of applications.

The User Group worked closely with JEDEC and IPC in the development of the JESD201 and JP002 documents. However, the tin whisker issue is not solved and continued emphasis on this topic remains important to the reliability of products. The current goals of the User Group are to maintain a focus on this issue and to continue to provide guidance to users and suppliers to minimize the probability of tin whiskers creating functional or reliability problems with our products. This result is achieved by a combination of known mitigation practices, process controls, and some level of testing. The tin whisker issue remains critical for reliability of electronic products. Billions of components are used annually, but it takes only a single defect to create a problem.

II. Background Statement

Unalloyed tin electroplating has a long history of whisker formation and growth that has resulted in reliability problems for various types of electronic equipment[1]. The predominant whisker mitigation strategy for more than 50 years has been the addition of lead (Pb) to the tin plating. Legislation has restricted the use of lead in electronic products sold in the European Union and many other areas of the world, and has resulted in electronic component suppliers removing Pb from tin-lead (SnPb) plating, leaving essentially pure tin. This approach is the most common and least costly lead-elimination strategy for the majority of component manufacturers. However, for the high-reliability user community, the pure tin strategy presents reliability risks due to the whisker forming tendencies of pure tin and tin alloy plating.

This report lists viable Pb-free finish alternatives for various applications. The positions presented are based on the personal experiences of the members taken in conjunction with the available technical literature on tin whisker formation and growth. The User Group also recognizes the ongoing work on whisker formation and growth carried out under the auspices of several consortia, including the iNEMI Tin Whisker Modeling Project, the iNEMI Tin Whisker Accelerated Test Project, and the University of Maryland's Computer Aided Life Cycle Engineering (CALCE) group (http://www.calce.umd.edu/lead-free/tin-whiskers/). Particular acknowledgement is made to the NASA Goddard Space Center website (http://nepp.nasa.gov/whisker/), which lists considerable background information on tin whisker problems and research.

Significant progress has been made in understanding whisker formation and fundamentals in the last few years. It is generally accepted that the driving force for whisker formation is compressive stress in the tin films[2]. This stress can be from numerous different sources, including intermetallic formation, oxidation and corrosion, thermal cycling, or mechanical sources. There remains much to understand to fully characterize the whisker formation and growth process. Quantitative models that allow prediction and characterization of whisker growth do not exist. As such, the mitigation practices and guidelines that follow have their foundation in prevention of compressive stress build-up in the Sn films and a substantial body of empirical data supporting their use. Additionally, standard test conditions and acceptance criteria have been created. However, these may or may not be accelerated relative to actual field use conditions nor can they be directly correlated to use environment and service conditions. Therefore, any claims for "whisker-free" tin-plating processes, or guaranteed lifetimes without a whisker failure, must be regarded with skepticism at this time. The User Group strongly encourages continued research on tin whisker issues and mitigation strategies.

III. General Guidelines for Migrating to RoHS-Compliant Finishes

There is a great deal of new information in the public domain on tin whisker formation and strategies for migrating to lead-free surface finishes[3]. It is advisable to be fully aware of the available data and alternatives before making any decision. Each firm needs to evaluate the alternatives in terms of reliability risk and cost benefits for the market application.

The user should be advised that whisker experimentation has been notoriously inconsistent relative to growth rates, incubation times, and many other parameters.

Nevertheless, certain whisker mitigation guidelines have been supported by the iNEMI User Group. It is important for the reader to understand that the various mitigation practices and techniques discussed here are not always effective in reducing tin whiskers and should not be construed as whisker prevention methods, but rather as whisker risk reduction methods. Other material sets and combinations may be considered by some users if strong technical arguments are provided as to why they are efficacious in reduction of tin whiskers, and are backed up with tin whisker test data. Alternative mitigation practices and/or tin whisker test procedures must be agreed upon by the specific users and suppliers. Table 1 in Section IV gives an order of preference for Pb-free finishes.

A. Commonly Available Mitigation Practices (in order of preference)

1. Non-tin plating: Nickel-palladium-gold (or just plain nickel-palladium) should be strongly considered for lead-frame applications. This plating has a long history (1992-present) of field application[4]. Early solderability issues have been resolved. In addition, NiPdAu is not prone to whisker growth in most environments. The iNEMI User Group strongly recommends this plating for most lead-frame applications to retard whisker growth. However, users should be aware that molding compounds do not adhere as well to noble metals, such as Pd and Au, as they do to copper. As such, it may be more difficult for NiPdAu packages to achieve MSL 1 and 2 performance at the higher temperatures associated with SnAgCu Pb-free assembly. NiPdAu has also exhibited corrosion in accelerated tests using high hydrocarbon and sulfur atmospheres. Such corrosion has not been noted in actual field conditions.

2. Adding Pb to Sn plating mitigates whisker formation[5]. Although not viable for many products due to legislation restricting the use of Pb, there are numerous exemptions and "out-of-scope" products that may still use SnPb finishes. This has been the primary means of tin whisker mitigation for over 50 years and has an excellent field history. The iNEMI User Group strongly recommends the continued use of SnPb plating in exempted applications. Suppliers are encouraged to continue manufacturing SnPb finished components for these applications.

3. Adding a nickel (Ni) underlay between tin plating and a copper (Cu) base metal mitigates whisker formation (this is a key User Group recommendation). The underlayer plating may alleviate the compressive stress in the tin film, which is thought to be one of the driving forces for tin whisker growth. The thickness, porosity and ductility of the nickel plating are also very important to ensure an effective barrier layer for the copper. It is important to ensure that the appropriate values for these parameters are met even after lead forming. If the nickel layer is cracked or damaged during subsequent forming or other operations, it has been demonstrated to be an ineffective mitigation technique[6]. Similarly, the control of the tin bath impurities, particularly copper, is important to make this underlayer effective[7,8,9]. Additionally, thin Sn films (up to 3µm) plated over a Ni barrier

layer may benefit from tensile stress generated in the Sn film from the NiSn intermetallic formation to partially compensate for compressive stresses generated from various other sources, such as thermal cycling[10].

4. The User Group accepts the use of a 150°C for 1 hour anneal within 24 hours of electroplating as a generally effective mitigation technique for tin-plated copper alloy lead-frames. Annealing/heat treating has been an accepted tin whisker mitigation technique[11,12,13,14,15,16,17,18,19,20,21,22] since 1962. Published authors generally recognize that annealing will increase the incubation time for whisker formation but delay times vary widely, from months to many years. Annealing may also reduce whisker lengths in comparison to non-annealed parts but the data is very sparse. Recent data[20-22] indicates that annealing changes the morphology of the intermetallic from an irregular Cu_6Sn_5 to a more uniform bilayer intermetallic compound consisting of Cu_3Sn and Cu_6Sn_5. Due to the variability in results it is recommended that annealing be accepted only when accompanied by supporting test data. Also see item number 23.

B. Other Viable Mitigation Practices, Less Commonly Available (roughly in order of preference – see Section IV Table 1 for order of preference)

5. Hot dip tin is a molten tin bath process that is not prevalent in lead-frame construction intended for electronic components, but it has been used for structural steel parts, connectors and devices such as relays[23,24,25,26,27]. There is evidence that this mitigation process may not be effective with pure tin[28]. Hot dipping with Sn-4%Ag or SnAgCu is generally an effective mitigation practice[29]. Hot dipping with SnCu alloy may or may not be effective. When plated tin finishes are dipped following plating as a mitigation strategy, there may be areas of the termination that are not covered because of part geometry. These areas will have a greater risk of tin whisker growth than coated areas.

6. Fusing tin plating shortly after plating mitigates whisker formation[30,31]. Fusing is a reflowing operation usually done by dipping the tin-plated surfaces into a hot oil bath. Some User Group members recommend fused tin based on excellent field history.

7. Plated SnAg (2-4% Ag) alloys in limited testing have shown promise in reducing tin whisker growth[22]. The User Group encourages further investigation of this finish as a possible tin whisker mitigation practice.

8. When added to tin in amounts of 2-4% by weight, bismuth may aid in suppressing whisker growth[32,33,34] and can be a viable mitigation practice. Users should be aware that SnBi finishes used on Alloy 42 leadframes and soldered with SnPb will result in reduction of the solder joint fatigue life compared to a SnPb finished lead soldered with SnPb[35,36]. This should be evaluated by the user relative to the acceptability in the given use environment. Concerns about tin-bismuth (SnBi) alloy finishes with low Bi concentrations in conjunction with

eutectic SnPb solder forming SnPbBi ternary eutectics are unfounded. There is a low melting point ternary eutectic formed between tin-lead-bismuth with a melting point at 96°C. However, it is not thermodynamically possible to form this ternary eutectic with small (1-5% by weight) additions of Bi to Sn finishes when soldered with SnPb [37]. There is a ternary SnPbBi peritectic that is thermodynamically viable for Bi above 6% by weight in the component finish, and this peritectic has a melting point of 135°C. As long as the Bi concentration on the lead is less than 6%, the peritectic should not be an issue. With eutectic tin-lead solder, it is necessary to control the bismuth content of the finish between 3-5% so as to have enough bismuth to suppress whisker formation without getting into the compositional range of the ternary eutectic. In addition, keeping the Bi content low is required to retain solderability of formed leads.

C. Finishes that Should Generally be Avoided (in no particular order)

9. Silver finishes are not prone to whisker growth in most environments. However, rapid growth of silver dendrites or, in some cases, silver whiskers may form in the presence of H_2S (found in some cases where the environmental air pollution contains SO_2) [38]. Additionally, users sometimes avoid silver finishes due to potential issues with electromigration and solderability shelf life.

10. Plated tin-copper alloys are not satisfactory finishes because copper enhances whisker formation and growth when included as an alloying element in tin plating[39]. See item 6 for dipped SnCu finishes.

11. The User Group strongly recommends against the use of tin plating over brass without a copper or nickel diffusion barrier plating[40,41,42,30,15,16,19]. If a copper underlayer plating is used, additional mitigation practices for tin on copper are recommended. The minimum thickness for the copper or nickel diffusion barrier should be 1.27 µm.

12. In general, bright tin plating is not recommended. However, there may be specific applications where bright tin is a viable solution. Bright tin plating is not recommended without a nickel barrier layer or for soldered applications (ICs, passives, etc.). For non-soldered applications, some recent studies show that whisker growth from bright tin may be suppressed when a Ni underlayer and newer, lower carbon content bright tin platings are used[43,44,45,46,47,48,49,50,51]. Note that not all references agree[52]. Given this, users may choose to evaluate bright tin over a Ni barrier for non-solderable applications. The nickel must be continuous and non-porous on all surfaces of the component. For components with internal cavities (e.g., BNC connectors) verification of the nickel plating thickness and coverage on the internal surfaces is critical. Historically, bright tin plating has been considered to be worse for whisker growth than matte tin plating[53]. Bright tins have typically had more than 0.8% carbon content and higher, as plated, compressive stress levels than matte tins. Traditional matte tin platings had larger grains and lower carbon content than bright tins. However, new bright tin

platings that have low carbon content and purportedly low stress are commercially available. The carbon content can be as low as that of matte tin. However, it is important to understand that this is a relatively new development and further investigation is encouraged. Controversy exists regarding the role of grain size and carbon content in promoting whisker formation. Each of these may contribute to the promulgation of compressive stress in the tin plating. Regardless of the selection of matte or bright finish, a tin whisker test (as defined by JESD201) should be performed to assess performance of the tin plating. The grain structure (see guideline 14) and data on the stress level of the tin film over time may be useful in evaluating the suitability of this finish. Additional investigation of these new low carbon content bright tins is encouraged. For the purposes of this document, matte and bright tin finishes are defined by the following:

Parameter	Matte Sn	Bright Sn
Carbon Content	.005%-0.050%	0.005%-1.0%
Grain Size	1µm-5µm	Less than 1µm

D. Mitigation Practices with Further Study Needed (in no particular order)

13. Adding a silver (Ag) underlay between tin plating and copper base metal has been proposed as a method to mitigate whisker formation, similar to Ni as noted above. However, there is limited whisker test data supporting the effectiveness of an Ag underlay for whisker mitigation[54]. The User Group acknowledges the potential for this mitigation practice to be effective, and encourages further investigation of this technique.

14. A non-columnar grain structure with a significant number of horizontal and oblique grain boundaries (ideally an equiaxial grain structure) in a tin finish may reduce or eliminate whisker growth by facilitating reduction of compressive stress by diffusion (rather than whisker growth)[55, 56, 57, 58]. The data confirming this mitigation technique is still very limited. The User Group encourages further investigation of this technique as a possible tin whisker mitigation practice. It is strongly recommended that the stress levels of tin deposits utilizing this technique be tracked over time and be confirmed to not build up in compressive stress over time.

15. Surface chemical etching prior to plating of copper-based alloys in limited testing has shown promise in reducing tin whisker growth when the etching depth is in the range of 3 to 4µm[59]. The User Group encourages further investigation of this technique as a possible tin whisker mitigation practice.

E. Applications of Concern

16. Corrosion (severe oxidation typically due to condensation of water) of Sn finishes has been theorized to be a significant source of compressive stress[60,58] in

Sn films and can drive whisker growth[61,62]. For applications where corrosion is a significant concern additional precautions, such as conformal coating or non-Sn finishes, should be considered in order to reduce the risk of tin whisker related failures.

17. Applications where a continuous mechanical compressive stress is applied to a tin finish (e.g., zero insertion force connectors on a flex cable interconnect) are particularly at risk for tin whisker growth and should be evaluated carefully by the user to determine if whisker growth in this application will result in reliability problems. Users should work with suppliers to find appropriate solutions in these applications.

18. Applications where significant thermal cycling occurs, such as power cycles, outdoor applications, etc., can create compressive stress in Sn finishes associated with the CTE mismatch of the Sn and base materials. Mitigation practices such as underlayer platings or annealing that address only the stress created by intermetallic formation are not effective for mitigating tin whisker growth in these applications.

19. Users should be cautious in using tin finishes on alloy 42 (Fe-42Ni) lead-frames in applications where there is significant thermal cycling. Sn(1-4%)Bi plating has shown promise in reducing whisker growth in this application. Additionally, low-porosity NiPdAu is available for this application from at least one lead-frame supplier.

20. Immersion tin is a chemical displacement process that results in a relatively thin (<40 micro-inches or 1µm) and stress-free tin film. Whiskers have been grown on immersion tin by iNEMI team members, but the whisker lengths are typically limited to <20 microns. For some applications, immersion tin is a suitable minimum risk selection that has been successfully used by some of the iNEMI User Group companies. Solderability shelf life considerations generally make this finish inappropriate for electronic components. It is, however, one of the lead-free finish options for printed circuit boards[63].

21. When Sn is plated over steel, mitigation practices should be used to lessen tin whisker risk. Recommendations for mitigation include using matte tin greater than 5µm thick in conjunction with annealing at 180ºC for 1 hour. (Other annealing times and temperatures may also be viable.) This can be done with or without a copper strike underlayer plating between the steel and Sn [64,65,66,67,68]. Nickel underlayer plating has also been reported to be effective on steel substrates[69]. The User Group also recognizes the applicability of annealing for tin plated on steel and brass as reported during the 1960s, 70s, and 80s [11-15]. Annealing temperatures ranged from 100-190°C and annealing times ranged from 9 hours (at 100°C) to 1 hour (at 190°C).

F. Other Considerations and Recommendations

22. The User Group does not recognize the circuit board assembly reflow process as a mitigation practice. There is no consensus in the open literature to support assembly reflow as an effective process for mitigating tin whisker growth. There has been some data published that suggests that the assembly reflow process can result in an increase in whisker growth on loose components[70,71]. Some whisker growth has also been seen on soldered components[72]. Partially reflowing plating on a given surface may increase whisker growth[73]. This mechanism is not understood at this time, but factors such as part geometry and reflow solder coverage are likely to confound the observed data. There is also some limited data that suggests assembly reflow can reduce whisker growth on Alloy 42 base materials[74,75,76].

23. Industry data indicates that thicker tin finishes show a lower propensity for tin whiskers and/or a greater incubation time before tin whiskers occur[72,77]. The User Group recommends tin thickness for components without a nickel or silver under-layer be at least 10µm nominal or thicker (8µm minimum preferred). When a nickel or silver under-layer plating is used, the minimum tin thickness should be 2µm to ensure solderability shelf life. Components that use nickel under-plating should have a porosity-free nickel thickness of a minimum of 0.5µm. Components using silver under-plating should have a minimum silver thickness of 2µm.

24. The use of conformal coating after assembly has shown some promise in reducing the rate of whisker growth. The effectiveness of this approach appears to be specific to the material types used and the environment. Data does not support conformal coating to be a cure for whisker growth. However, it does add an insulation barrier that may prevent shorting should long whisker growth occur[78,79].

25. The macro stress level of the tin deposit has an impact on tin whisker growth[80]. Tin deposits that have tensile stress as plated and remain tensile with aging are preferred. Tin deposits that are compressive during service life are not preferred.

26. The effect of bias voltage and/or current on whisker growth is not well understood. In limited testing, there have been mixed results on the effect of bias on tin whisker growth[81,82,83]. Bright tin has shown a significant bias effect on whisker growth in one test, but none on matte tin in the same test[84]. One field failure for whisker growth on a bright tin also suggests that bias has an effect on whisker growth[85]. However, in a number of unpublished tests on matte tin finishes, no effect of bias has been seen. Given the data currently available, the User Group does not believe that the effect of electrical bias on whisker growth is a significant concern, and does not recommend any additional testing of tin finishes for whisker growth with either electrical bias or current.

27. Since a full understanding of the tin whisker growth mechanism is still lacking, collecting data on the characteristics of tin plating is critical to help increase the knowledge level on parameters affecting tin whisker growth. JESD22A121.01, Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes, defines data collection requirements for tin finishes. The User Group recommends data collection in accordance with that standard.

IV. Electronic Component Lead and Terminal Finishes

Electronic component lead and terminal finishes refer to the solderable finishes applied to electronic components. These include lead-frames for ICs, leads for other solderable components, terminations for discrete components, and solderable finishes applied to plated covers on electronic components. Lead-frames are the metal tabs that electrically connect the chip die to the printed circuit board. The majority of current lead-frames are made of copper or a copper alloy. In addition, some lead-frames are still made of an iron-nickel alloy (e.g. alloy 42). Typically, the lead-frames are purchased without a finish (or plating) and processed at the manufacturing site into a package. Tin lead-frame plating is done after the molding operation. Historically, the predominant lead-frame finish was a tin-lead alloy with typical nominal Pb content ranging from 7% to 37% Pb. However, this transitioned primarily to tin-based Pb-free alloys in the 2005/2006 timeframe. About 10% of the lead-frame finishes are NiPdAu, which is purchased in a pre-plated form by the component assembly manufacturer.

Table 1 (below) lists all the lead-free finishes that the User Group has identified as offered or proposed finishes for electronic components. For each finish, which includes under-layer plating if applicable, and associated base material, the finishes are placed in one of three categories. This table is specific to tin whiskers and does not directly address other possible issues and concerns with these finishes. Category 1 indicates that the proposed solderable finish will be accepted by the User Group without any tin whisker testing. Category 2 indicates that the finish will only be accepted if it passes the whisker test requirements given in JESD201, Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes. Previous data generated according to the iNEMI Tin Whisker Acceptance Test Requirements may also be acceptable to users. A Category 3 rating indicates that User Group members consider this finish a high risk for tin whiskers and will not accept it in any case, regardless of tin whisker test data provided. The table summarizes what the majority of companies will accept for each finish. Suppliers should be aware that though this table represents the majority opinion, individual company requirements may vary.

Table 1: Component Lead-Free Finishes (Tin Whisker Test Requirements)

Solderable Finish	Base Material		
	Cu (7025, 194, etc) (excluding Brass)	**Low Expansion Alloy (Alloy 42, Kovar)**	**Ceramic (such as resistors and capacitors) – no lead-frame**
	Category	Category	Category
NiPdAu	1	1	1
NiPd	1	1	1
NiAu	1	1	1
Hot Dipped SnAgCu	1	1	1
Matte Sn w/ Nickel underplate	2	NA	1 or 2 (1)
Reflowed Sn	2	2	2
Matte Sn w/Silver underplate	2	2	2
Hot Dipped SnAg	2	2	2
Hot Dipped Sn	2	2	2
SnAg (1.5-4%Ag)	2	2	2
Matte Sn – 150C anneal	2	2	2
SnBi (2-4% Bi)	2	2(2)	2
Hot Dipped SnCu(7)	2 or 3(6)	2	2
Matte SnCu – 150C anneal (2% Cu)	3	3	3
Bright Tin w/Nickel underplate	3(5)	3(5)	3(5)
Matte Sn	3(4)	2	3(4)
Semi-Matte Sn	3(4)	3(4)	3(4)
SnCu	3(4)	3(4)	3(4)
Bright Tin	3(4)	3(4)	3(4)
Ag (over Ni)(3)	1	1	1
AgPd (over Ni)(3)	1	1	1
Ag (3)	1	NA	1

Category 1: No tin whisker testing required
Category 2: Finish must pass tin whisker testing
Category 3: Do not accept this finish in any case

Color Coding for Table 1:

- (green) Preferred finishes
- (light blue) Finishes with preferred tin whisker mitigation practices
- (yellow) Finishes with tin mitigation practices that are less desirable than preferred practices
- (orange) Finishes without tin whisker mitigation that are often not acceptable to users
- (red) Finishes to avoid

Notes for Table 1:

(1) In general, tin whisker testing is required. However, users have accepted for approximately 10 years, and many will continue to accept, small discrete resistor and capacitor device components with a matte Sn over Ni finish. These devices are exceptions to the tin whisker test requirements but must meet all of the following criteria to be acceptable:
   - The Sn finish shall be matte tin as specified above (See Section III, item 12)
   - The Ni under layer shall be at least 2µm (80 micro inches).
   - The supplier shall have data to substantiate control of its processes to minimize whisker growth (see JESD201).
   - The devices must not require any lead forming or other stress creating operations after final finish.
   - Tin plating thickness greater 2µm (80 micro inches) is the minimum acceptable.
   - New component types must be similar in size and construction to previously accepted components.
   - Plating of new component types must use the same plating lines, chemistries, etc. that have been previously accepted.
   - New component types must pass whisker testing unless otherwise agreed to by user and supplier.

(2) A number of users have restrictions on the use of SnBi finishes on alloy42 leadframes that are independent of tin whisker concerns. See Section III, item 8 for more information.

(3) In general, although whiskers on Ag and AgPd finishes are not considered an issue, the User Group is very hesitant to accept these finishes due to a number of concerns including, but not necessarily limited to, electromigration and solderability shelf life.

(4) A small number of users may accept these finishes for devices with lead spacing greater than 1mm.

(5) Some exceptions exist where users may consider this option. See Section III, item 12 for more information.

(6) There is significant disagreement among users as to whether this finish is acceptable, regardless of whisker test results.

(7) Factors such as part geometry and solder coverage that result in thin areas of the finish may play a significant role in the tin whisker mitigation effectiveness of this finish.

V. Separable Connectors

A separable connector is defined as a make/break connector with a separable interface for interconnection and, typically, a second interface with a more permanent connection, such as a crimp to a wire or a solder joint to a PCB. Separable connectors include, for example, compliant pin connectors, bolt-on connectors, PCB connectors and cable connectors. Separable connectors usually have a nickel underlay beneath a film of gold, tin-lead, or pure tin.

Many connectors use tin as a solderable finish and use a precious metal in the separable interface. If the tin plating is completely wet during the soldering process, the likelihood for whiskering after soldering is greatly reduced. Thus, some companies may have different acceptance criteria for tin used only in the solderable interface.

Compliant pins (or press-fit pins) utilize a contact design where a portion of the contact is mechanically inserted into a plated through-hole (PTH) of a printed circuit board. The EU RoHS Directive has an approved exemption for the use of Pb in compliant pin terminations. As exemptions are to be reviewed every four years, this exemption may eventually be eliminated.

Compliant pins typically utilize a tin-lead plating to achieve reasonable insertion forces. Members of the User Group have performed testing on lead-free compliant pins and shown that the insertion forces and retention forces increase when the Pb is removed from the finish. This increase in insertion force is acceptable in most applications. The increase is most strongly linked to the switch from bright tin-lead coatings to matte tin coatings. Bright tin coatings have demonstrated insertion forces that are statistically equivalent or lower than bright tin-lead; however, any tin plating over nickel should be reviewed for whisker performance in a stress induced application.

Whisker growth can be accelerated by the high stresses exerted on terminal finishes used on bolted connectors. Bolted connectors are typically annular rings (ring lugs) that are bolted down onto a base metal, often with a Belleville washer assembly to maintain a high torque level over time. Many of these products have used pure tin finish for decades and many of them have generated tin whiskers. Each application must be analyzed relative to possible exposure to sensitive electrical circuitry. For example, bolted connections in the air stream leading to electrical circuitry could be considered a sensitive location. Whisker forming materials should not be used in sensitive locations.

Table 2 (below) summarizes the iNEMI User Group's ratings for connector finishes relative to concerns about whisker formation and growth. The first column tabulates acceptance of finishes for solderable terminations. The second column tabulates the use of surface finishes in a region of the product where the terminal finish is in the stressed separable interface and the connector spacing is "fine". We define "fine spacing" as contacts with a spacing less than or equal to 0.5mm. The third column tabulates the use of surface finishes in a region of the product where the terminal finish is in the stressed separable interface and the connector spacing is "large". We define "large spacing" as contacts with spacing greater than 0.5mm.

Table 2: iNEMI Ratings for Whisker Risk on Termination Finishes for Separable Connectors

Finish	Termination finish use only as a solderable finish	Terminal finish use as a separable interface for fine spacing applications	Terminal finish use as a separable interface for large spacing applications
NiAu	1	1	1
NiPd	1	1	1
NiPdAu	1	1	1
Ag (over Ni)*	1	1	1
Hot Dipped SnAgCu	1	1	1
Reflowed Sn	1	2	2
Hot Dipped Sn	1	2	2
Hot Dipped SnCu	1	2	2
Matte Sn w/ Nickel underplate	2	2	2
Matte Sn w/Silver underplate	2	2	2
Matte Sn – 150C anneal	2	2	2
Matte SnBi (2-4% Bi) w/Nickel underplate	2	2	2
Matte SnAg (1.5-4%Ag) w/Nickel underplate	2	2	2
SnCu w/Nickel underplate	2	2	2
Bright Tin w/Nickel underplate	2	2	2
Matte SnBi (2-4% Bi)	2	2	2
Matte SnAg (1.5-4%Ag)	2	2	2
Matte Sn (no underplate)	3	3	2
Bright Tin	3	3	3
SnCu	3	3	3

1) No tin whisker testing required
2) Finish must pass tin whisker testing
3) Do not accept in any case

Color Coding for Table 2:

- (green) Preferred finishes
- (light blue) Finishes with preferred tin whisker mitigation practices
- (yellow) Finishes with tin mitigation practices that are less desirable than preferred practices
- (orange) Finishes without tin whisker mitigation that are often not acceptable to users
- (red) Finishes to avoid

Note for Table 2:
*In general, although whiskers on Ag finishes are not considered an issue, the User Group is very hesitant to accept these finishes due to a number of concerns including, but not necessarily limited to, electromigration and solderability shelf life.

VI. Bus Bars

Bus bars are typically copper or copper alloy. Aluminum may also be used in some applications. These parts are of particular interest because they are usually in close proximity to electrical circuitry. Whiskers on these assemblies can cause problems if they dislodge and short electrical circuitry. It is, therefore, prudent to avoid using plating material that is susceptible to whisker formation and growth. If possible, it is advisable NOT to plate bus bars when the application allows. In non-corrosive environments, the base copper metallurgy will tarnish slightly over time, but the basic function of the piece will be unaffected. Localized plating to enhance solderability or contact resistance should utilize platings other than tin when possible, or utilize tin whisker mitigation practices. Table 3 summarizes the recommendations of the iNEMI User Group.

Table 3: Bus Bars – Tin Whisker Concerns

Finishes	Solderable (Yes/No)	Base Materials	
		Copper Alloys (excluding Brass)	Aluminum
None (unfinished)	No	OK	OK
Nickel	No	OK	Over Copper Strike Plating OK
Chromium(3)	No	OK	Over Copper Strike Plating OK
SnAgCu Solder Dip	Yes	OK	Over Copper Strike Plating OK
Silver(1) (Immersion or Electroplate)	Yes	OK	Over Copper Strike Plating OK
Matte Sn(2)	Yes	Not Recommended(2)	Over Copper Strike Plating, Not Recommended (2)

Notes for Table 3:
(1) Silver (Ag) plating, while frequently used for bus bars, is susceptible to corrosion in sulfurous environments or dendritic growth in the presence of moisture.
(2) When utilized on bus bars as a finish, tin whiskers are a concern for this finish, particularly when bus bar connections result in mechanical stresses on the finish. As such, the iNEMI Tin Whisker User Group recommends that this finish not be used for bus bars. If Sn finishes are used, a tin whisker mitigation practice is recommended. This finish has been used on bus bars in many products for years,

so the application may still be acceptable even with tin whiskers. It is up to the user to make the final decision as to acceptance of this finish.

(3) Chromium finishes should not contain CrVI (Hexavalent Chrome).

VII. Heat Sinks

Heat sinks are commonly aluminum (including anodized aluminum), copper, or graphite. Graphite heat sinks are generally unfinished and tin whiskers are not a concern with graphite. Copper heat sinks generally require a finish, and may require solderability on some portion of the finish. Similarly, if aluminum heat sinks require soldering, they are typically selectively plated or solder dipped to provide a solderable surface. Lead-free plating finishes that utilize Sn are a concern for tin whisker growth as the use of heat sinks is typically associated with electronic components. Tin-based lead-free finishes should not be used when the heat sink finish is subjected to mechanical mounting stresses. Table 4 summarizes the recommendations of the iNEMI Tin Whisker User Group relative to heat sinks.

Table 4: Heat Sink Finishes and Tin Whiskers

Surface Finish	Solderable Surfaces (Yes/No)	Heat Sink Base Material		
		Aluminum	Copper	Graphite
None (or anodized for Aluminum)	No	OK	OK	OK
Nickel	No	NA	OK	NA
SnAgCu	Yes	OK (Over Cu Strike)	OK	NA
Matte Sn over Nickel	Yes	(Over Cu Strike) Tin Whisker Testing Required (1)	Tin Whisker Testing Required (1)	NA
Matte Sn	Yes	(Over Cu Strike) Not Recommended(1)(2)	Not Recommended (1)(2)	NA

Notes for Table 4:

(1) Tin whisker testing required per JESD201.

(2) This finish is generally not recommended due to tin whisker concerns. However, it may be acceptable if one of the preferred mitigation practices is used (see Table 1). Also, if the matte Sn surface is fully wetted by solder during assembly, the finish is generally acceptable.

VIII. Printed Circuit Boards (PCBs)

The surface finish on PCB lands (made of copper) are designed to protect the base metal against oxidation that could result in poor solder joints during assembly operations. HASL (hot air solder leveled) tin-lead finishes have been the coating of choice for most of the last fifty years. To comply with legislation, alternative Pb-free surface finishes must be considered. These finishes include organic solder preservatives (OSPs), immersion gold over electroless nickel, electroplated gold over electroplated nickel, Pb-free HASL, immersion silver, and immersion tin. Of these surface finishes, immersion tin is susceptible to the formation of pure tin whiskers and immersion silver is susceptible to the formation of silver sulfide dendrites. Both tin whiskers and silver sulfide dendrites can create electrical shorts; however, the formation mechanisms and the required environmental conditions are different. There have been no reported instances of tin whiskers on SnCu HASL finished PCBs. However, it should be noted that the use of SnCu HASL as a board finish has been very limited. For all of these finishes, individual processes vary tremendously relative to film quality, corrosion resistance, shelf life, etc., and the user should work closely with the process provider to evaluate each particular process. Aside from whisker and dendrite growth, other aspects of the surface finishes will affect selection, including cost, shelf life, solderability, manufacturability, corrosion resistance, and technical limitations with certain assembly processes, component types, and board designs.

Table 5 summarizes the assessments of the individual members of the iNEMI Users Group relative to the above PCB finish processes.

Table 5: Printed Circuit Boards

PCB Finish	Tin Whisker Test Requirements?
SnCu HASL	Yes
Immersion Sn	Limited
Electroless NI/Immersion Au	None
Electroplated NI/Electroplated Au	None
Immersion Ag	None
OSP (e.g. Entek)	None

IX. Future Work

The iNEMI User Group meets regularly to consider implications of new data on tin whiskers. Changes and revisions to this position statement will be made as new data that warrants changes becomes available.

X. iNEMI Contacts

Parties interested in participating in iNEMI activities should contact Ronald W. Gedney (703-834-0330 or rgedney@AOL.com) for information. There are currently three ongoing iNEMI project teams focused on tin whisker issues:

a. Tin Whisker Modeling Project - Chairman: Dr. George T. Galyon, IBM Corporation
b. Tin Whisker Accelerated Test Project - Chairman: Dr. Heidi Reynolds, Sun Microsystems
c. User Group - Chairman: Joe Smetana, Alcatel-Lucent

In addition to the projects on whisker fundamentals and testing, there are also ongoing iNEMI initiatives dealing with lead-free assembly operations and materials.

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