ASSESSMENT OF WHISKER GROWTH FROM TIN COATED WIRE AND CABLE

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ABSTRACT

Pure tin is a common finish for copper hook up wire, coaxial cable, ground braid and harness assemblies used on electronics assemblies. Historically there have been few reports of tin whisker growth on tin coated copper wire, even on unjacketed wire. This paper presents data on past incidences of whisker growth on wire as well as analysis of wire samples of various size and age. Based on a limited sample size, the data indicate very low risk for whisker growth on tin coated copper wire, braid and cable.

Key words: tin coating, tin whisker, wire, braid, cable, intermetallic compound.

INTRODUCTION

It is well documented that bulk tin materials, as well as dipped and plated layers of tin, spontaneously generate hair-like conductive surface growths known as "tin whiskers." Whiskers develop in any environment: ground or vacuum/space, wet or dry, applied power vs. no power. The time period before whiskers start to grow from a tin surface, known as the "incubation period," can vary between minutes and decades.

The purpose of this paper is to address the question, "What is the risk for whisker growth on tin-coated wire?"

Twenty samples of single-stranded tin-coated wire and braid, manufactured between 1965 and 2008, from 10 different suppliers, were analyzed by Scanning Electron Microscopy (SEM) and Energy Dispersive Xray (EDX) to evaluate the material composition, size and density of whiskers. In addition, two samples were temperature cycled for 1000 cycles between -40 and 100°C. Wires were cross sectioned to evaluate the effects of intermetallic compound and tin layer thickness.

No tin whiskers were observed on any of the samples; only burrs were observed on several tin plated cable braid samples.

The data suggest that several factors including geometry, thickness of tin layer, and post plating annealing and cold working processes combine to mitigate whisker growth on re-drawn tin plated wires.

SPECIFICATIONS AND LITERATURE DATA

Pure tin is a common coating on bus wire, stranded wire, coaxial cable, and ground braid products. Several commercial and military specifications call out tin coating, including MIL-DTL-17, AA-59551 (superseding QQ-W-343), NEMA-WC27500 (superseding MIL-DTL-27500) and SAE-AS22759 (superseding MIL-W-22759).

Citations of whisker growth on tin plated wire and cable are sparse. A literature search, summarized in the References section, uncovered a few instances of whisker growth that may be relevant to tin plated wire. Various types of tin coated samples were analyzed at Bell Labs in the 1950s and 60s. Arnold (ref 9) showed pictures of whiskers on a tin coated wire support in a resonator. On tin coated wire, "*Only short whiskers, relatively few in number, were found*" (ref 10). The NASA Goddard tin whisker website (ref 11) includes photos of whiskers on diode wire leads, tin-plated waveguides and phosophor bronze test points made from cut and formed plated wire. There were allegorical references to whisker growth on tin plated copper wire in references 5 and 8, but no hard data or images. Wire manufacturers cited only a handful of customer reports of whiskers growing from tin coated wire over the past 20 years, all on type H wire.

Several references suggest that there is little to no risk for substantial whisker growth on tin coated wire and cable.

Laboratory studies of tin-coated wire on Titan missile harnesses found no whiskers (ref 2, 3, 4). In 1992, MIL-STD-1547 ("Electronic Parts, Materials and Processes for Space and Launch Vehicles rev B," ref 6) was revised to include an exemption for tin plated drawn wire products, such as cables, shielding and ground straps. All other types of tin plated components were prohibited from use on space and launch vehicles. A recent update to this standard (Aerospace Corp. TOR-2006-8583-5236, ref 7) also allows for the use of tin-plated wire in high reliability applications.

ANALYSIS

To evaluate the risk for whisker growth on tin-coated wires and cables, twenty samples of tin plated wire, cable and braid were sampled and analyzed by scanning electron microscopy (SEM), energy dispersive x-ray (EDX) and cross section. EDX was performed to verify the pure tin finish and base material, then visual inspection was performed at high magnification by SEM.

Table 1 summarizes the wire part numbers, dates of manufacture, and storage conditions. Samples were drawn from two laboratories in which wire spools had been stored in controlled temperature and humidity conditions. In one of the labs, a fortuitous find was a stash of tin plated wire spools dating back to the 1960's, including stock originally procured by TRW and Space Technology Labs.

All of the wire samples were uninsulated bus wire, coax cable or braid where the tin surface was fully exposed to the storage environment. Samples were taken from the outer part of the spool. Jacketed wire was not evaluated because it was not clear how stripping off the jacket for inspection would affect tin whiskers. For comparison, a tin copper solder lug was included in the analysis.

Figure 1 shows an example of EDX analysis data on a single-stranded tin coated copper wire. All 20 samples were confirmed to have pure tin coating over copper with no other elements detected.

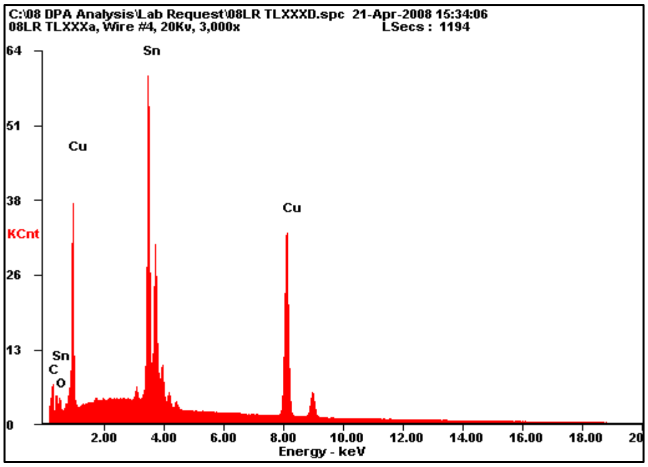

Figure 1. EDX data on sample #4, confirming copper wire coated with pure tin.

None of the 20 wire and braid samples showed whiskers. On braid samples, some flat strands were observed on the surface (see Fig. 3) but they was believed to be "burrs" incurred from the manufacturing process or from stands rubbing together.

Figures 2 and 3 show SEM images of tin coated wire and braid samples, respectively. By contrast, Figure 4 shows a SEM image of an electroplated tin coated copper terminal lug, exhibiting profuse whiskering. The samples in Figures 2-4 were fabricated in the 2002-2007 time frame.

To evaluate the IMC and tin coating thicknesses, 14 samples were submitted for cross section, including 8 bus wires, 4 braids, a coax cable and a solder lug. Table 2 summarizes the measurements and Figures 4-6 are cross section images.

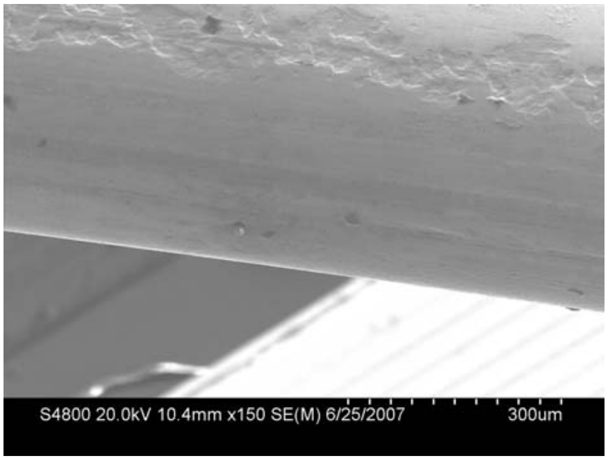

Figure 2. SEM image of surface of sample #18, post 1000 thermal cycles. Small plating imperfections and protrusions were observed, but the surface was relatively clean with no cylindrical shaped whiskers.

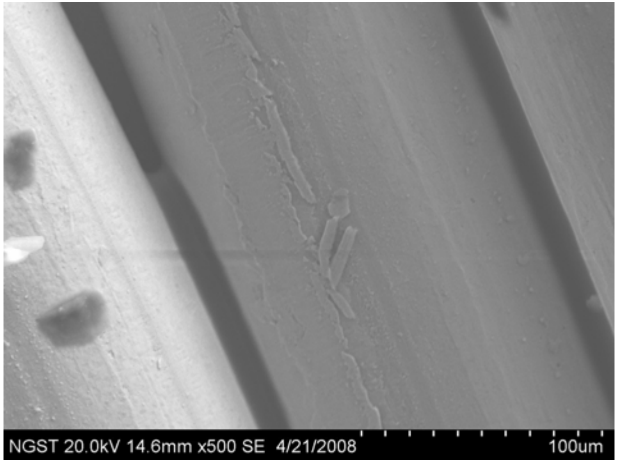

Figure 3. SEM image of sample #6 tin plated copper braid. No whiskers were observed. Multiple thin flat strands were characterized as "burrs," most likely generated during the braiding operation or flexing of the braid.

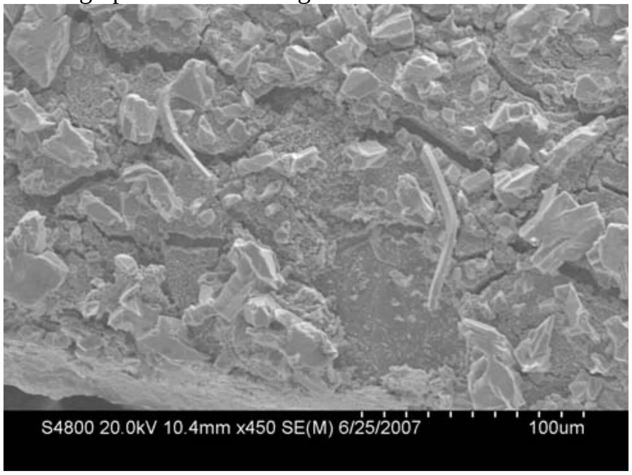

Figure 3. SEM image of sample #23 tin plated copper lug. Irregular crystal structure and whiskers are visible in the image. High densities (approx. 40 to 80 whiskers/mm^2) of medium-length whiskers (maximum length 75 um; typical length 20 to 30 µm) were visible on the surface especially at holes and edges.

Sample i.d.	Description	Supplier	Location	Year of Manuf	Storage Conditions	Analysis
1	QQW343S24S1T tin coated bus wire	Blake	NGIS Rancho Carmel, CA	2007	Stored uncovered on spools, controlled temp & humidity	• EDX confirmed pure tin coating • No whiskers detected in SEM inspection • Irregular surface contour
2	22-1-7C tin coated bus wire	Blake		2002		
3	C252583-222 tin coated bus wire	unk		unk		
4	QQB575R36T0500 tin coated ½” braid	Cont. Cordage		2007		• EDX confirmed pure tin coating • No whiskers detected in SEM inspection • Burrs detected but believed to be caused by mechanical action
5	1188 tin coated 1/8” braid	Belden		1986		
6	100-C02A1000 tin coated 5/8” braid	Glenair		2007		
7	EW88180 tin coated bus wire	Unk	NGAS Redondo Beach, CA (Space Technology Labs heritage)	1968	Stored in closed drawer on spools, controlled temp & humidity	• EDX confirmed pure tin • No whiskers in SEM
8	ES600 tin coated 1/16” braid	Alpha		1968		• EDX confirmed pure tin • No whiskers in SEM • Burrs detected
11	QQ-W-343 type H, 16 AWG tin coated bus wire	Belden		1966		• EDX confirmed pure tin coating • No whiskers detected in SEM
12	EO8237R QQW343 type H 20 AWG tin coated bus wire	Victor		1965		
13	Tin coated bus wire	MWS		1965		
14	QQW343 type S 24 AWG tin coated bus wire	Camden		1982		
15	EW-8815 tin coated bus wire	Victor		1965		
16	MIL-DTL-17/133 tin coated copper semi-rigid cables	TIM-CO	NGIS Rancho Carmel, CA	1995	Stored uncovered, controlled temp & RH	• EDX confirmed pure tin coating • No whiskers detected in SEM
17					1000 temp cycles -40 to 100°C	• EDX confirmed pure tin coating • No whiskers detected in SEM
18	QQW343S22S1T 22 AWG tin coated copper bus wire	Blake		2002	1000 temp cycles -40 to 100°C	
19	EW8812 14 AWG tin coated bus wire	National	NGAS Redondo Beach, CA (Space Technology Labs heritage)	1966	Stored in closed drawer on spools, controlled temp & RH	
20	QQW343 Type S 26 AWG tin coated copper bus wire	Blake		1995		
21	C260796-001 QQB575 tin coated copper 1/8” braid	Blake		2003		
22	QQB575R30T1000 tin coated copper 1” braid	Cont. Cordage		2008		
23	MS35431-1 tin coated copper lug	Zierick	NGIS Rancho Carmel, CA	2002	Stored in controlled temp & RH	• EDX confirmed pure tin • Multiple whiskers detected in SEM

Table 1. Analysis of Tin Plated Wire, Braid and Cable Samples

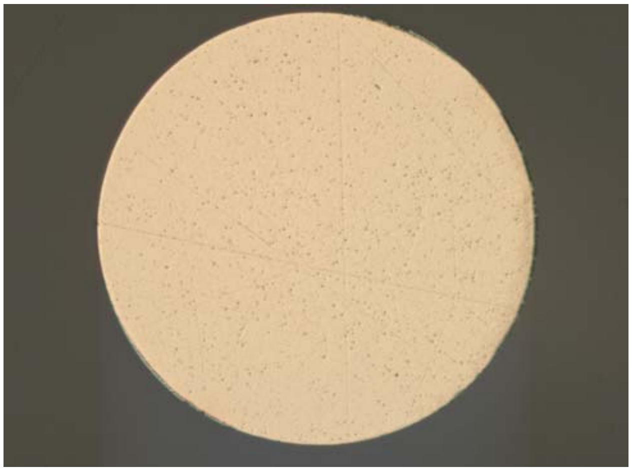

Figure 4. Optical image of sample #12 cross section. Tin plating is uneven and barely visible at this magnification. Copper wire is 20 AWG (nominal .032” diameter).

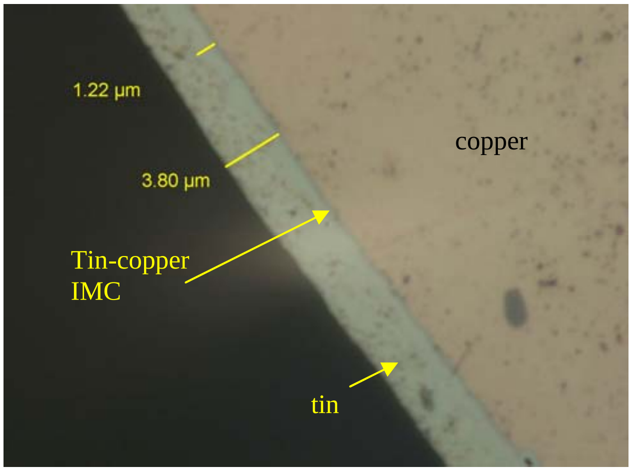

Figure 5. Optical photo of sample #12 cross section showing tin, IMC and copper.

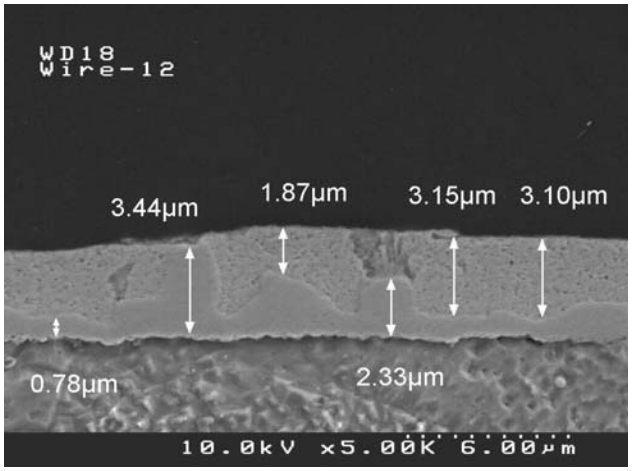

Figure 6. SEM image of sample #12 cross section shows tin + IMC thickness of 3.2 to 3.8 um over copper. IMC thickness is irregular, varying between 0.8 um and 3.4 um and completely consuming the tin at some places. Note the difference in materials’ appearance, tin and copper being porous and pitted while the IMC is smooth.

Sample i.d.	Total wire diameter	Surface layer thickness	Tin-copper IMC thickness
2	.025”	1.5 to 1.9 um	0.5 to 1.9 um
4	.0043”	2.7 to 2.9 um	0.4 to 0.9 um
5	.0059”	0.5 to 0.8 um	0.5 to 0.8 um
11	.051”	4.4 to 7.1 um	1.1 to 2.2 um
12	.033”	3.2 to 3.8 um	0.8 to 3.4 um
14	.020”	5.1 to 5.3 um	0.7 to 3.5 um
15	.032”	0.5 to 0.7 um	0.6 to 0.7 um
17	.117”	18 to 21 um	1.6 to 5.1 um
18	.025”	0.8 to 1.1 um	0.8 to 1.1 um
19	.064”	1.3 to 1.5 um	1.3 to 1.5 um
20	.016”	3.5 to 4.2 um	0.5 to 0.7 um
21	.0059”	1.1 to 1.5 um	1.1 to 1.5 um
22	.0094”	0.8 to 1.1 um	0.8 to 1.1 um
23	.018”	18 to 25 um	2 to 5 um

Table 2. IMC Thickness Measurements

In summary, for a quantity 20 sample size, there was no correlation between whisker growth and age of sample, wire diameter, coating thickness or IMC thickness.

DISCUSSION

Tin plated wire and cable samples analyzed in this study, aged for up to 44 years, were not susceptible to whisker growth. This begs the question, what makes tin plated wire and cable different from tin plated component leads and terminations, which readily grow whiskers?

Literature studies identify several possible drivers for the difference:

- Intermetallic growth between the copper and tin (ref 6, 7, 8, 10)
- Stress relief due to heat exposure (ref 3)
- Stress relief due to cold working (ref 3)
- Plating bath chemistry (ref 10)
- Coating thickness (ref 10)

Coating Thickness and Intermetallic Compound. Two intermetallic compounds (IMC) form between copper and tin, Cu_6Sn_5 and Cu_3Sn. The tin plated copper wires in this study did not have a diffusion barrier layer, such as nickel, so the copper and tin were free to interdiffuse and form binary compounds at the interface. IMCs grow over with time and temperature. There are two schools of thought on the effects of IMCs: most modern references assert that IMC growth increases the stress on tin surface layers and is a driving force for tin whiskers, while a second hypothesis is that IMCs suppress tin whisker growth (ref 6,7,8,10).

Tin coating thickness on the samples varied between 0.5 and 25 um. Most of the solid wire products sampled were purchased to U.S. Federal Specification QQ-W-343, either type S or H (the QQ spec was canceled in 2000 and superseded by Commercial Item Description A-A-59551).

QQ-W-343/A-A-59551 type S single stranded wire complies with ASTM B33 for tin coated soft or drawn and annealed copper wire. ASTM B33 does not specify a tin coating thickness but requires that the "tin coating shall be continuous." Wire manufacturers stated that the tin coating on type S wire is 40 uin (1 um) thick minimum. One micron of coating is thick enough to protect the underlying copper and prevent corrosion but limits the shelf life of the wire. Type S wire with 1 um coating will not pass a solderability test after steam aging and under normal storage conditions; its solderability degrades after a few years. This is due to oxidation of IMCs once they reach the surface.

QQ-W-343 type H wire is commonly called "hookup wire." Type H wire also complies with ASTM B33 for coating requirements, however, there is an additional solderability requirement levied on type H wire. The solderability test, per MIL_STD-202 method 208, calls for steam age preconditioning. To meet this requirement, wire manufacturers fabricate type H wire with much thicker tin coating, typically 300 uin (7.7 um) or more.

Four of the bus wire samples and three braids had tin coating thickness less than 2 um, these roughly correspond to QQ-W-343 type S wires. The type S wires older than 5 years old had no perceptible tin left on the surface; all tin had been converted to tin-copper IMC. The tin layer on type S samples from 2002 and 2007 were almost all consumed (70-90% on the surface layer composed of IMC). The conclusion is that the tin on type S wires is consumed within a few years after manufacture which may be a factor in the lack of whiskers observed.

Four wires and one braid had tin thickness in the range 3 to 7 um, more consistent with QQ-W-343 type H. These samples showed pure tin at the surface, even dating back to 1965, with IMC consuming between 15 and 45% of the tin coating. Figure 7 plots average IMC thicknesses measured on the 14 cross sectioned samples as a function of the sample age. As expected, the data show a general trend of increasing IMC thickness with age. Outliers in Figure 24 are samples 17 and 23 which have much thicker tin coating (20 um) than the other samples.

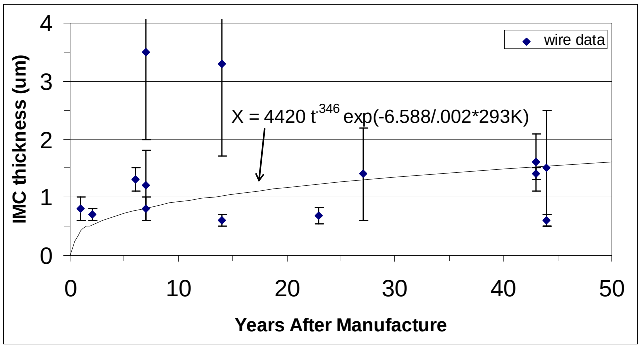

Figure 7. Intermetallic thickness measured on tin plated copper wires as a function of age. Solid line reflects predicted tin-copper IMC growth based on data presented by Stephens (ref 1).

Elevated temperature processes or very long times are needed for tin coatings to be completely consumed by IMC. At room temperature, it takes more than 10 years for tin-copper IMC to grow to 1 um thick. At tin reflow temperatures, it takes only 5 to 10 minutes.

Figure 8 shows a trend between IMC content and type of tin coating, either type S (thinner) or type H (thicker). The tin coating on type S wires will be quickly consumed by IMC, whereas type H wires will retain about 75% of its nascent pure tin at the surface. Thus IMC growth on wires with thin tin coatings (type S) is a factor in suppressing whisker growth since all of the pure tin coating is consumed.

The fact that none of the 20 type S nor type H wire samples grew tin whiskers means that there are other forces driving whisker growth and suppression besides IMC related phenomena. In addition, there was no correlation between whisker suppression and age of sample. These conclusions are supported by recent experimental findings that strain gradients in the tin layer are more of a driving force for whisker growth than the presence of IMC or compressive stresses (ref 13).

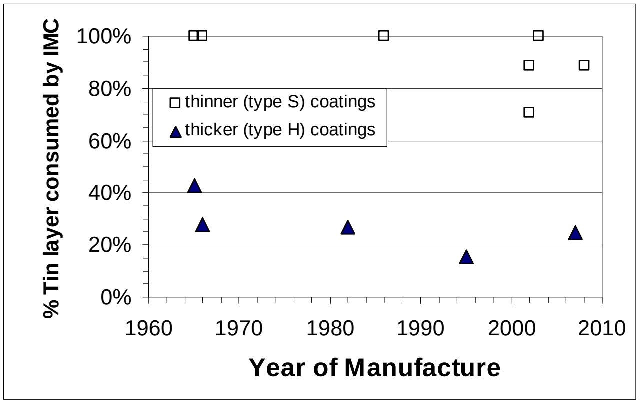

Figure 8. Percent of tin surface layer consumed by IMC on tin coated copper wires. The tin coating on type S wires is completely consumed by IMC, whereas type H wires retained 50 to 75% of its nascent pure tin at the surface.

Wire Manufacturing Processes: Coating and Working. Two processes are used to coat bare copper wire with tin: electroplating (aka electrodeposit) and hot dipping. Plating is an electrochemical process; the copper wire acts as the cathode on which tin ions, dissolved in the electrolytic plating bath solution, deposit to form the coating. Hot dipping is a physical process of passing the copper wire through a bath of molten tin.

General steps to the coating processes are illustrated in Figures 9-11. Regardless of the coating process, the bare copper wire is processed the same. Copper rods or bars are heated and drawn through a series of diamond-coated steel dies to reduce to the desired diameter. Drawing is similar to extrusion except that the wire is pulled through the die rather than pushed. Depending on the desired temper, the

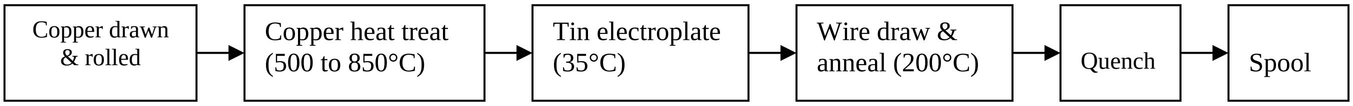

Figure 9. General processes used to fabricate type S electroplated tin plated copper wire.

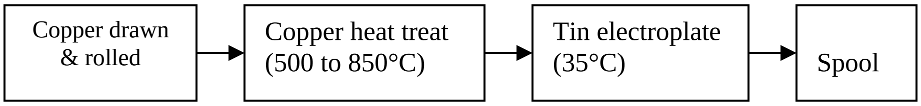

Figure 10. General processes used to fabricate type H electroplated tin plated copper wire.

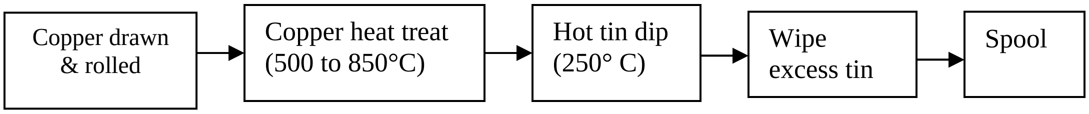

Figure 11. General processes used to fabricate type S hot dipped tin plated copper wire.

wire is heat treated or annealed after draw. The wire is coated and spooled.

There are significant differences in the way that type S and type H electroplated wire are processed. For type S, tin is plated on a larger wire, typically 12 AWG, then the plated wire is drawn down to the desired finished size and annealed before spooling. By contrast, type H wire is drawn to final size prior to plating and does not get re-drawn after plating.

Post-coating processing steps for type S hot dipped wire may vary by supplier, but usually a handling step, such as a manual wipe-down, is necessary to remove excess tin. Hot dipping is not an option for manufacturing type H wire. Hot dipped tin gives a more shiny appearance than plated tin which has more dull gray appearance.

Twenty years ago, hot dipping was the more popular tin coating process, but in recent years, electroplating has grown in popularity. It is estimated that 70% of the tin plated copper wire on today's market is electroplated. According to wire manufacturers, unless the method for type S coating is specified by the customer, the method (i.e. electroplating or hot dip) will depend on the equipment and capacity of the specific manufacturing site.

Significant differences between hot dipping and electroplating are

1) Hot dipping takes place at much higher temperature, therefore resulting in thicker initial IMC.
2) Hot dipped wire is handled in the molten state to remove excess tin; processes may be variable.
3) Type S electroplated wire is drawn through a die after plating to ensure the desired dimensions and annealed, whereas type H electroplated wire is not re-drawn and not always annealed after the plating process.

All of these factors carry significance in suppressing whisker growth. The post-plating drawing steps cold work the wire; annealing also relieves stresses in the plating. The larger IMC layer in hot dipped wire results in less pure tin material available for whisker growth. Thus type S wires (hot dipped or electroplated) would tend to be at lower risk for whisker growth than wires with thicker plating (type H). QQ-W-343 and AA-59551 include the statement "Type S wire used for hookup and interconnect wire is superseded by typeH, class S wire." Type H wires are indeed preferred as hookup wire on electrical assemblies because of its solderability. In terms of whisker mitigation, however, type S wire is preferred to type H.

Plating Bath Chemistry. A variety of chemistries are used for tin electroplating. Organic brighteners are sometimes added to plating baths to enhance the visual appearance of the tin deposit. The chemistries used on the samples analyzed in this study were not traceable, therefore the effects of different tin chemistries were not quantified. Grain size or structure was also not evaluated in this study.

Tin Plating on Wire vs. Components

Reports of tin whisker growth on component terminations, including surface mount, through-hole, leaded and leadless parts, and mechanical parts such as washers and shims, are commonplace. So what are the differences between these parts and tin plated wire?

Table 3 summarizes features of component plating vs. wire plating. Three differences are

1) Components are usually electroplated with 2 to 5X thicker tin layer than wires.
2) Components leads are often not worked after plating.
3) Component terminations usually have sharp edges and corners, whereas wire is round.

None of these three factors (thick plating, cold working or geometry) appear to be a cure-all for whisker growth. Whiskers have been observed to grow on cylindrical leads, parts with thin plating and samples that are annealed or worked after plating. However the combination of factors appears to be effective in suppressing whisker growth.

General consensus among subject matter experts interviewed during the study was that the post-plate working operations were the most likely cause for whisker mitigation in wires.

The tin layers on samples 17 (tin plated copper coax cable) and 23 (tin plated copper lug) are about the same thickness (20 um), yet sample 17 grew no whiskers and sample 23 showed a multitude of whiskers. This may be attributed to the fact that sample 17 saw post-coating operations; sample 23 did not.

Factor	Wire	Component terminations
Base material	Copper	Copper, alloy 42, Kovar, other
Geometry	Round, no edges	Typically rectangular with sharp edges & corners.
Coating thickness and underplate	Type S < 2 um Type H 5-10 um Tin coating directly over copper	5 to 20 um Often a nickel diffusion barrier
Coating process	Hot tin dip or electroplate followed by wire draw--composition & controls vary by supplier	Electroplated
Heat exposure /anneal	Yes, copper is annealed prior to plating. Type S and H annealed after plating.	Most cases: no
Cold working	Yes, copper is repeatedly drawn prior to plating. Type S electroplated wire is drawn after plating	Most cases: no. Some leads are formed after plating
IMC growth	Thicker for hot tin dipped tin coatings. Thinner for electroplated coatings.	Thinner for electroplated coatings. Thicker is part is reflowed or annealed.

Table 3. Tin Coating on Component Terminations vs. Wire

SUMMARY AND CONCLUSIONS

SEM/EDX inspections and composition analyses were performed on 20 tin plated wire and cable samples from 10 different suppliers manufactured between 1965 and 2008.

- No tin whiskers were observed on any of the samples; only burrs were observed on tin plated braid samples.
- Since no whiskers were observed, there was no correlation between whisker growth and age of sample, intermetallic compound thickness, supplier or coating process (hot dipped vs. electroplated).
- Significant differences between tin plated wire (no whiskers) and tin plated component terminations (whiskers) include geometry, thickness of tin layer, and post plating annealing and cold working processes. None of these factors alone appear to be completely successful in suppressing whiskers; rather it is likely a combination of factors.
- The literature contains four reports of whisker growth on tin plated copper wire or wire leads (refs 8,9,10,11), but no detail on the processing of the wires. Similarly, interviews with wire manufacturers revealed isolated reports of tin whiskers on wire over the past 20 years.
- Several data-based references state that there is little to no risk for substantial whisker growth on tin-plated wire and cable. Laboratory studies of tin-coated wire on Titan missile harnesses found no whiskers on the wire (ref 2, 3, 4). MIL-STD-1547 (“Electronic Parts, Materials and Processes for Space and Launch Vehicles rev B,” ref 6) includes an exemption for tin plated drawn wire products; all other types of tin plated components were prohibited from use on space and launch vehicles.

The data support the conclusion that whisker growth is greatly diminished on pure tin plated bus wire, stranded wire, ground braid, and other products that undergo post-plating drawing operations as part of their fabrication.

This study was conducted on a relatively small sample size of 20; the reader is encouraged not to conclude that all tin-coated wire is immune from tin whiskers.

Whisker suppression in tin electroplated wires is due to a combination of relatively thin plating, geometry (no sharp edges) and post-plating processing operations that may relieve stresses in the tin layer.

In hot tin dipped and electroplated wires with thin (type S) tin coating, whisker suppression is likely enhanced due to IMC growth that consumes the tin layer a short time after manufacture.

It can be concluded that electrodeposited and redrawn tin plated wire, braid and cable products can be used on high reliability hardware with no further steps necessary to mitigate tin whisker growth.

REFERENCES

No.	Reference	Statement on Tin Plated Wire
1	J.J. Stephens, “Prediction of Long-Term Growth Kinetics for Cu-Sn Intermetallic Phases in Bulk Specimens,” Sandia National Labs internal memo, March 1989.	Gives data on Cu-Sn intermetallic growth as well as recommended equation for predicting IMC thicknesses.
2	Aerospace Corp. Product/Process Problem Alert Bulletin (APAB) 9202, May 1992. “The Formation and Impact of Tin Whiskers” by J.H. Richardson. Also GIDEP Problem Advisory BA-P-92-01 July 1992.	“All electronic and mechanical parts and materials coated with tin are susceptible to formation of tin whiskers…NOTE: The one exception to the general exclusion on tin plating is tin coated copper wire. Studies by one Air Force contractor has indicated that this wire, used in insulated wires, braided grounding straps, and braided shielding is not a source of tin whiskers.”
3	Air Force Memorandum A3-207-DWB/MRB-92-96, from D.W. Bridges to R.L. Ramsauer, 11 August 1992. “Air Force Acceptance of Tin-Coated Copper Wire for Use on Titan Wire Harnesses.”	The contractor cited in the GIDEP BA-P-92-01 is MDSSC (McDonnell Douglas Space Systems Corporation) who issued a laboratory report summarizing metallographic studies performed on tin-coated copper wire from Titan harnesses…”since any stress in tin-coated copper wire has been dissipated by hot wire drawing and annealing during its manufacture, Titan wire harnesses are tin-whisker free.”
4	McDowell, M.E. "Tin Whiskers: A Case Study, (USAF)", Aerospace Applications Conference, pp. 207 -215, 1993.	"Despite the preponderance of evidence that tin-on-copper creates whiskers, tin-coated copper wire has never exhibited whisker growth.”
5	NASA Parts Advisory NA-044, 1998. “Tin Whiskers” by M.J. Sampson.	Based on experience, the following commodities appear to be the ones most at risk for whisker formation. Particular attention to these commodity types is suggested: relays, connectors, filters and bus wire. Pure tin coated wire is recommended for solder applications only. Tin whisker growth is only a risk in areas where the insulation has been removed and the wire has not been coated with solder.
6	MIL-STD-1547 (USAF), Electronic Parts, Materials and Processes for Space and Launch Vehicles, Rev B, (superseded) 1992.	2.6.3 Tin Coated Wire. Tin or tin alloy is the least expensive, but is susceptible to oxide film formation and corrosion when exposed to traces of chlorine, oxides of nitrogen, or humidity. Tin whisker formation may be possible but not probable due to alloying of the thin tin coating with the copper of the wire. 4.3.3.1 Pure Tin Coatings. Mechanical parts, mounting hardware, optical and electronic parts and their packages shall have neither internal nor external surfaces coated with a pure tin or tin alloy layer. **4.3.3.3 Exception: This prohibition does not apply to drawn wire products, such as cables, shielding and ground straps.**
7	Aerospace Corp. Report No. TOR-2006(8583)-5236, “Technical Requirements for Electronic Parts, Materials, and Processes Used in Space and Launch Vehicles,” November 2006.	4.3.3.1 Pure Tin (plating or coating). No pure tin, or >97% tin by weight, shall be used internally or externally, as an under-plating or final finish in the design and manufacture of the space vehicle, including (but is not limited to) EEEE parts and their packages/ terminals/leads, mounting hardware, solder lugs, EMI shields, and spacecraft structures. Tin shall be alloyed with a minimum of 3 percent lead (Pb) by weight. (c) **Tin plated wire may be used provided that for each lot of wire, all the tin has been converted to copper tin intermetallic as demonstrated by chemical analysis.** Prohibited parts list includes tin plated wire and braid.

8	SAE Aerospace Information Report AIR5444, 1998. "Investigation of Whisker Formation on Tin Plated Conductors," prepared by SAE Wire and Cable subcommittee AE-8D.	4.1 There have been several instances of whisker growth on tin-coated copper conductor. These instances have been limited to bus wire applications where the conductor had no surface insulation. No documented observations of tin whisker growth on insulated tin plated copper wire was found in published literature. The SAE AE-8D subcommittee was surveyed….Of the 19 respondents…No respondents had direct information on cases of whiskers in wire and cable. 5.2 Tin coated copper conductors usually contain a relatively thin coating of electroplated tin on the surface of the conductor strands. It is a well-documented phenomena that diffusion of copper and tin forms a copper-tin intermetallic….It is conceivable that this change in composition of the surface from pure tin to intermetallic tin effectively removes the conditions necessary for whiskers to form.
9	S.M. Arnold, "Growth of Metal Whiskers on Electrical Components," Proceedings of Electrical Components Conference, pp. 75-82, 1959.	Gives an example of a tin-coated "wire support" (no indication of base metal) inside of a resonator.
10	S.M. Arnold, "Repressing the Growth of Tin Whiskers," Plating, pp. 96-99, January 1966.	"Many samples of tin-coated copper wire were then examined. Only short whiskers, relatively few in number, were found. It was thought that possible diffusion of the copper into the tin was responsible for this reduction in whisker growth."
11	NASA Goddard tin whiskers web site http://nepp.nasa.gov/whisker/photos/index.html#testpoint	Contains photos of tin-plated phosophor bronze test points and waveguides with small whiskers. Test points are made from a plated wire that is cut and formed.
12	Personal communication/email from H. Leidecker and J. Brusse, NASA GFSC, November 15, 2007.	"…reports of whiskering of tin-coated copper wire produced as 'bus wire' or 'lashing wire' are unknown to us… "We HAVE(!) seen whiskers growing from tin-plated copper lead wire."
13	M. Sobiech, M. Wohlschlögel, U. Welzel, E. J. Mittemeijer, W. Hügel, A. Seekamp, W. Liu, and G. E. Ice, "Local, submicron, strain gradients as the cause of Sn whisker growth", Applied Physics Letters, 94, 221901, June 2009.	A popular hypothesis has been that the driving force for whisker growth is mechanical compressive strains in the Sn coating developed during and/or after layer production and thus whisker growth can be regarded as a strain relief phenomenon. Compressive strains in the Sn coating develop upon aging at room temperature due to intermetallic phase formation at the Cu/Sn interface. Only very recently, experimental evidence indicated that compressive strains are not a prerequisite for whisker formation, but that, instead, the strain *gradient* in the direction from the surface of the Sn layer to the intermetallic compound region must be negative. Thus, whisker growth can occur in the presence of a tensile strain in the surface region of the Sn layer. Experiments have shown that local *in-plane residual strain gradients* occur around the root of spontaneously growing Sn whiskers on the surface of Sn coatings deposited on Cu.