IFA
Institut für Arbeitsschutz der
Deutschen Gesetzlichen Unfallversicherung

Tin whiskers on printed circuit boards

Consequences for safety components in machine construction

1 Problem

Safety components intended for use in the safety functions of machines frequently employ electronics and therefore printed circuit boards (PCBs). Short-circuits on these PCBs, caused for example by tin whiskers, may result in dangerous failure of safety functions, and must therefore be prevented from occurring.

Tin whiskers are needle-like forms of tin. They primarily occur on surfaces with a lead-free tin coating. Figure 1 shows an image from an optical stereo microscope at 40x magnification. Two pins of an integrated circuit (IC) package are visible; a tin whisker 270 µm in length has formed on the left-hand pin.

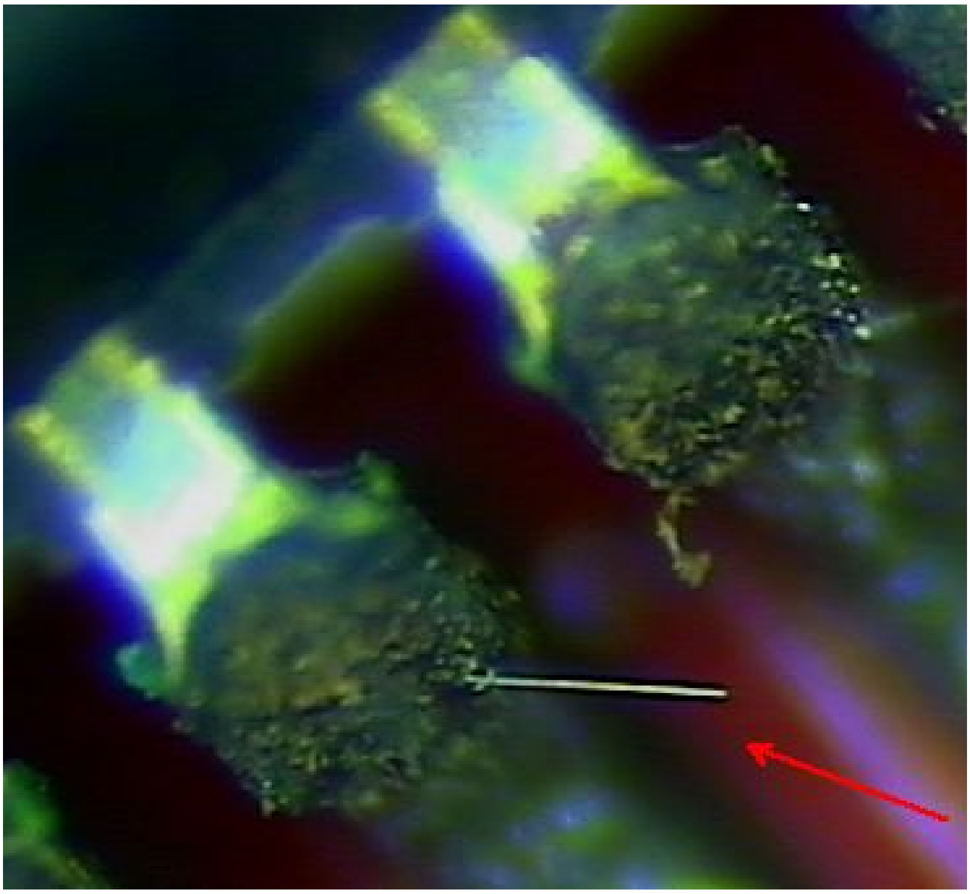


Figure 1: Tin whisker (270 µm) on an IC pin, 40x magnification, source: IFA

In Figure 2, several tin whiskers are visible under the scanning electron microscope (SEM).

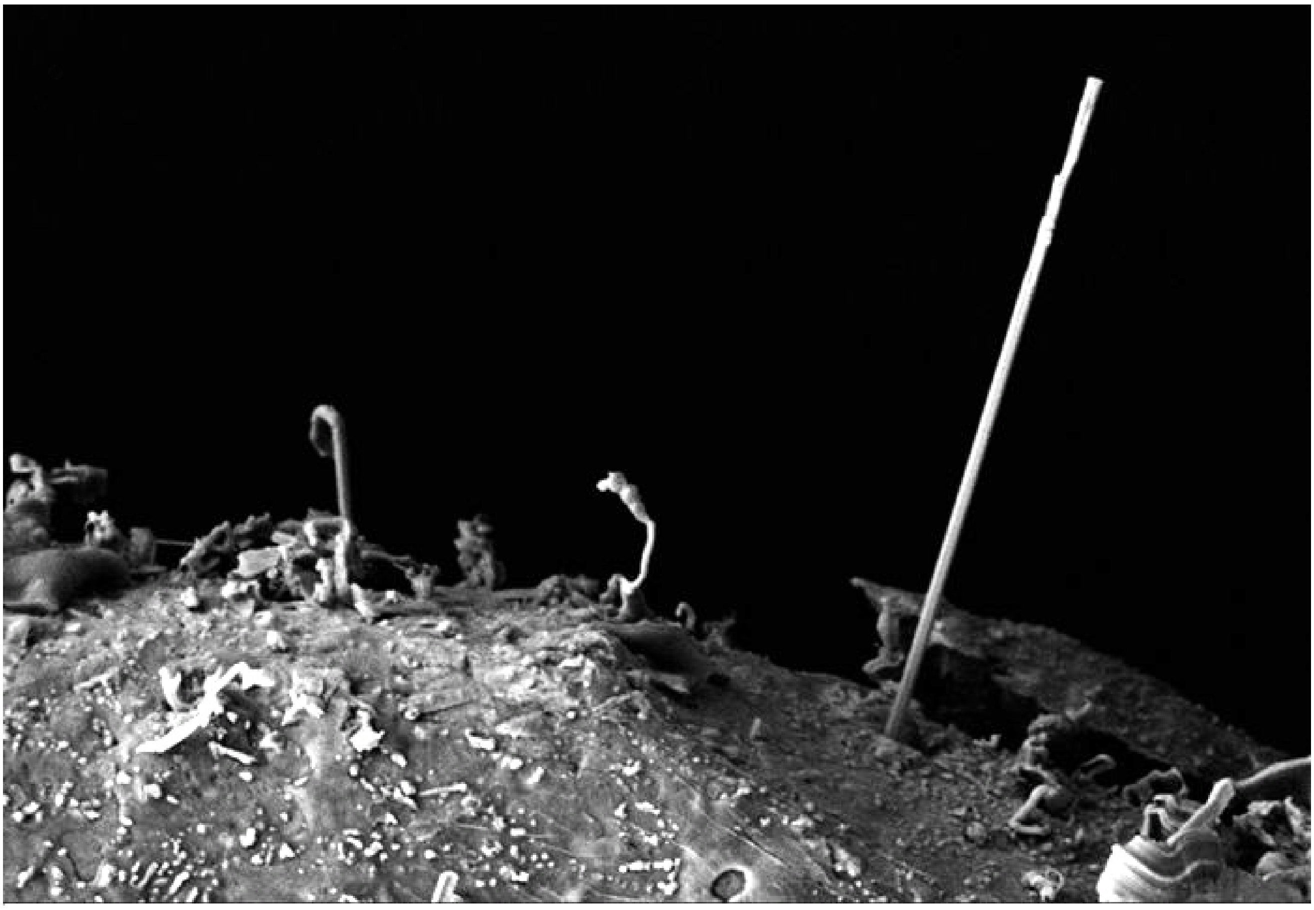


Figure 2: Tin whiskers under the scanning electron microscope

Tin whiskers may arise as a result of:

- External mechanical stresses
- Internal mechanical stresses
    - in the tin coating
    - in the pins, which are then transferred to the tin coating
- High temperatures
- High atmospheric humidity

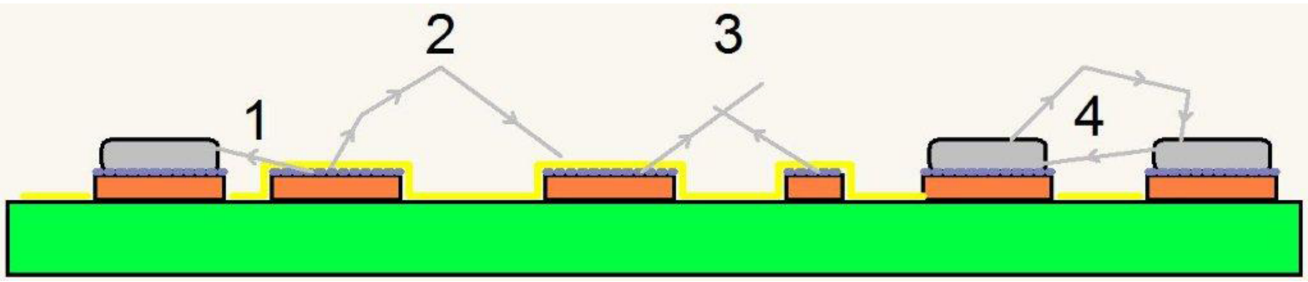
Tin whiskers have a length of up to 1 mm and in extreme cases up to 2 mm. At tin coated current bus-bars whiskers with a length of 10 – 20 mm were found. Tin coated current bus-bars with higher voltages and with one tin whisker are sensitive to produce an electrical arc [1]. They are conductive and can cause short-circuits on populated PCBs. A short-circuit current of 10 to 50 mA may flow through a whisker until, at the maximum current that the whisker is able to withstand, it ruptures rather than fusing.

Progressive miniaturization has resulted in the distances between component terminals falling to a few 100 µm – a distance that can easily be bridged by tin whiskers. Owing to their decreasing current consumption, the electronic circuits have also ceased to have a self-cleaning effect; tin whiskers are not generally destroyed by the short-circuit current flowing through them.

In the past, the formation of tin whiskers on PCBs was prevented by the addition of lead to the solder. In extreme situations a whisker growth was also found. Following adoption of the RoHS Directive [2], manufacturers now switched to the use of lead-free solder for the soldering process. The PCBs are populated with electronic components the terminals of which are suitable for lead-free soldering. As a result of this change, the formation of tin whiskers has been observed on populated PCBs. This gives rise to the following potential failures:

- A whisker growing out of a tinned trace (conductor pathway) may grow through the solder stop (a varnish which protects the traces against dirt and moisture) and cause a short-circuit to an adjacent solder point or component terminal (Figure 3, whisker 1).
- Whiskers can grow out of a stop layer but cannot penetrate the layer again, as they break off in the process (Figure 3, whisker 2).
- The likelihood of two whiskers growing out of different tinned traces and meeting (Figure 3, whisker 3) is very low, but cannot be excluded. The risk increases with the number of whiskers found.
- The risk of a short-circuit is highest between two adjacent solder points or component terminals (Figure 3, whisker 4).
- Whiskers can also grow out of the component terminals themselves.

Should several whiskers that have broken off be present on a PCB, they may also cause a short-circuit if their position is unfavourable.



green = PCB; bronze = trace; grey = tin coating, solder point; yellow = solder stop

Figure 3: Possible short-circuits on a PCB caused by whisker growth

The conditions under which tin whiskers are formed are currently the subject of heated debate. It is also not known precisely what measures prevent the formation of tin whiskers with lead-free soldering. Nor can the timing of their formation be predicted. This has been confirmed by the literature and also by a project conducted by the IFA [3] in which it was possible for tin whiskers to be grown on PCBs. Many measures can reduce or delay the whisker growth, the whisker length or whisker quantity. They can also reduce the whisker's length. The whisker growth can start or restart at any time, because the whisker growth depends on several random variables [1]. When designing their PCBs the manufacturers of safety components apply rules which are intended to prevent the incidence of short-circuits between:

- Two traces
- A trace and a component terminal
- Adjacent component terminals
- Terminals of different components

These rules are set out in EN ISO 13849-2:2013, Table D.5 [4] and EN 61800-5-2:2008, Table D.2 [5]. With the advent of lead-free soldering, this fault exclusion is now placed in doubt, since short-circuits are possible even when the rules cited are applied, owing to the formation of tin whiskers. The two standards already address this issue; owing to a lack of specific measures which could permit fault exclusion, however, attention is merely drawn to it.

In principle, short-circuits caused by tin whiskers can be prevented by further design measures, for example by the application of a further protective layer to the populated PCB including the solder points and component terminals. This however has drawbacks from a manufacturing point of view which are rarely tolerable.

The absence of fault exclusion of short-circuits on PCBs would have considerable repercussions for the assessment of their safety. A fault analysis would have to assume short-circuits at all possible adjacent points of a PCB. These short-circuits could lead to undesired changes to the electronic circuit the effects of which could not easily be predicted. Nor would the short-circuits necessarily be detected by the diagnostics measures which may be in place for safety functions. Owing to the scale and complexity, fault analysis is virtually impossible. The IFA therefore proposes a different procedure for dealing with the issue of whiskers. This procedure will be described below.

Note: this procedure is not yet in use in type examinations.

2 Concept for the consideration of tin whiskers

Component faults may influence the behaviour of safety functions even in the absence of short-circuits caused by tin whiskers. This possibility is already considered during the validation of safety functions. What is new however is that not only may faults occur within one channel of a safety function, but that two redundant, independent channels may be "connected" to each other by tin whiskers. For the additional consideration of faults caused by tin whiskers, it is therefore sufficient to consider only the points between channels at which they could potentially be short-circuited to each other. Suitable measures taken in these areas are not sufficient to prevent the formation of tin whiskers as such; they can however control their impact upon safety functions. The result is a fault model for tin whiskers on PCBs that is dependent upon the architecture (the Category to EN ISO 13849-1) of the circuit and which, when suitable measures are taken in certain areas of the PCB, permits fault exclusion for short-circuits.

The fault model is presented and the reasoning explained below, with reference to the whisker project of the IFA [3].

3 Consequences for PCB design

It must be assumed that tin whiskers may in principle form at all points containing tin and free of lead.

3.1 Reducing whisker formation

The formation of whiskers can be reduced, i.e. partially prevented. For safety-related PCBs, the following basic measures are effective:

PCB:

- No tinning of traces (no tin – no tin whiskers); alternatively, treatment with electroless (electrode less) nickel immersion gold, electroless silver or nickel (whisker barrier)
- Additional treatment of solder pads with electroless nickel immersion gold, electroless silver or nickel (whisker barrier)

Components:

- Use if possible of IC packages without bent terminal pins (e.g. flat packs), in order to avoid mechanical stresses in the pins
- Use if possible of nickel-plated, silver-plated or gold-plated terminals (whisker barrier)

Soldering process:

- Use of SnAgCu alloy as the solder (whisker barrier)
- If pure tin is used as the solder, use of matt rather than gleam finish (lower whisker growth)
- Use of anti-whisker additives in the solder
- Tempering of populated PCBs for one hour at 150 °C immediately following the soldering process (eliminates internal stresses from the tin)

Ambient conditions of the PCB in operation:

- Avoidance of installation of the PCB under mechanical stress
- Supporting of heavy components in order to avoid mechanical stresses
- The component temperature should be ≤ 70 °C (consideration of self-heating)
- The relative atmospheric humidity should be ≤ 80%
- Elimination of vibration as far as possible

  Note: These measures can only reduce the whisker growth but not eliminate it.

3.2 Additional fault model for PCBs

The tin whisker has the geometry of a needle; in extreme cases, it may reach 2 mm in length. Whiskers generally occur with a length of up to 1 mm. A fault analysis on a lead-free soldered PCB must therefore assume that whisker growth is possible from any solder pad and any component terminal pin within a spherical volume with a radius of 1 mm. This has not yet been considered in the fault model for PCBs in standards [4] and [5], and must be corrected.

Short-circuits caused by tin whiskers on PCBs may have effects upon safety functions, for example causing a dangerous failure in which the safe response is no longer possible despite being requested. In principle, this is true for all faults in components forming part of a safety function, and not just for short-circuits on PCBs. When a safety function is designed in accordance with to EN ISO 13849-1, the behavior in the event of component faults is already considered. Depending upon the required design Category for a subsystem within a safety function, component faults must be detected and/or must not lead to dangerous failure of the safety function (Categories 2, 3 and 4). In Category B and 1 circuits (in both cases single-channel), the safety function may fail dangerously as a result of a component fault; the additional "short-circuit caused by tin whisker" failure mode does not change this. "Well-tried components" are however used in Category 1 which in some cases are considered well-tried only if the design of the component permits fault exclusions. This is the case for example for an electromechanical position switch with positively opening contact (see Table D.3 in [4]). If however a tin whisker has short-circuited the terminals of the position switch on a PCB or has created a connection to the supply voltage, a dangerous failure of the safety function concerned has nevertheless occurred despite the positive opening of the contact in the position switch; the fault exclusion has therefore been negated. The additional fault model for tin whiskers on PCBs must therefore also be applied for Category 1 circuits. Tin whiskers do not need to be considered for Category B circuits.

3.2.1 Tin whiskers in two-channel safety functions

In two-channel circuits (Categories 3 and 4) and single-channel circuits with a supplementary test channel (Category 2), distinction must be made regarding the point at which a short-circuit occurs. Where a whisker short-circuit affects only one channel, the effects upon the safety function are largely identical to those of other component faults, which must already be considered during validation of the safety function, irrespective of the whisker issue. A whisker can however also cause a short-circuit **between two channels**. This constitutes a new failure mode, since the two channels are usually located separately on the PCB, and when the "short-circuit between adjacent traces/contact points" fault exclusion in accordance with standards [4] and [5] is applied, a component fault cannot lead to the two channels being connected. In addition, the signals of two channels must for example never be processed in the same IC, since a fault within the IC could otherwise cause both channels to fail dangerously at the same time. Exceptions exist only for safety-related application-specific integrated circuits (ASICs), which however are subject to special requirements.

Should a short-circuit caused by a tin whisker now connect two channels together, completely new electronic circuits are created, and the effects upon the safety function can be determined only with considerable effort. The single-fault tolerance for example may be lost, the detection of component faults may be rendered ineffective, and the safety function may fail dangerously. Owing to the large number of possibilities, the "short-circuit between two channels" failure mode is impossible to control in practical terms. In order for Category 2, 3 and 4 safety functions to be achieved despite this, measures must be found which prevent this fault from occurring.

3.2.2 Exclusion of the "short-circuit caused by tin whisker-fault" on PCBs

No means is known at the present time of reliably preventing the formation of tin whiskers on PCBs soldered without the use of lead. The resulting short-circuits can however be prevented by design measures:

- Coating to IEC 60664-3
  Coatings to IEC 60664-3 [5] are applied to PCBs in order to protect them against pollution. A whisker may grow out of the coating but not penetrate it, as it breaks off in the process. For the coated areas (which usually include the components), a short-circuit can therefore be excluded.
- Adequate clearances between the channels
  It is assumed that whiskers may generally grow to up to 1 mm in length. A short-circuit may therefore be excluded for all clearances > 1 mm.

Based upon the considerations described here, a proposal for extension of the fault model for PCBs has been developed which could be adopted within the standards [4] and [5] (see table).

Table: Additional fault model for PCBs

Fault assumption (in addition to EN 13849-2:2013, Table D.5/EN 61800-5-2:2008, Table D.2)	Fault exclusion	Remarks
Short-circuit between traces/solder pads/conductive surfaces/components by a tin whisker in Categories 1, 2, 3 and 4 (see i) Further information can be found in Comments 1 to 3.	Short-circuiting caused by tin whiskers can be excluded when: a) The PCB has been soldered with the use of lead (≥ 5% lead); or b) A coating to IEC 60664-3 has been applied to the components and the PCB; or c) Measures in accordance with ii) for the prevention of whisker formation have been applied and the clearance between traces/solder pads/contact points/components is ≥ 1 mm; or d) The measures in accordance with ii) for the prevention of whisker formation have been applied and the component terminals are not bent ("flat no lead" package, e.g. DFN, TDFN, UTDFN, XDFN, QFN, TQFN), or the components have nickel-, silver- or gold-plated terminals; or e) The clearance between traces/solder pads/conductive surfaces/components is ≥ 2 mm	1) Tin whiskers may form on surfaces tinned without lead (such as solder pads, tinned traces) and component terminals. Where measures in accordance with ii) for the prevention of whisker formation are taken, the affected points can be limited to bent, tinned terminals of components. Tin whiskers have a needle-like geometry and may be straight or bent, with a total length of up to 1 mm and in extreme cases up to 2 mm. 2) Whisker growth is possible beginning at any tinned point on a PCB, including the components with which it is populated, within a spherical volume with a radius of 1 mm (where measures in accordance with ii) are taken) or 2 mm (where they are not). 3) It is unlikely that two whiskers will meet and thereby cause a short-circuit between two safety relevant channels (redundancy). This possibility need not therefore be assumed.

i) It is sufficient to assume this fault only in the following cases:

I. Category 3 or 4:
- Short-circuit caused by a tin whisker between two function channels
- Short-circuit caused by a tin whisker between the sole function channel (single-fault tolerance achieved for example by fault exclusions) and traces/solder pads/conductive surfaces/components in the vicinity

II. Category 2
- Short-circuit caused by a tin whisker between function and test channel

III. Category 1
- Short-circuit caused by a tin whisker between terminals of (well-tried) components and between the function channel and traces/solder pads/conductive surfaces/components in the vicinity

Reasoning: in Categories 2, 3 and 4, short-circuits within a channel generally have the same effects upon a safety function as component faults within a channel, and as such are already considered. Additional possibilities for faults arise however as a result of short-circuits between components in different channels, or between a safety-related channel and "uninvolved" components. In Category 1, electromechanical contacts may be bridged by tin whiskers at the points of connection on the PCB, or a short-circuit may occur, for example to the supply voltage. The fault exclusion applied in some cases to the well-tried components in Category 1 for the failure of positively opening break contacts to open would be rendered ineffective as a result.

ii) (Systematic) measures for reducing tin whiskers for safety-related PCBs

PCB:

- No tinning of traces; alternatively, additional treatment with electroless nickel immersion gold, electroless silver or nickel
- Additional treatment of solder pads with electroless nickel immersion gold, electroless silver or nickel

Plug connectors, terminal plugs and terminal sockets:

- If redundant safety-related signals are relayed by these components, they must not be located directly adjacent to or above/below each other; adequate separation or additional isolation between the terminals is necessary.

Soldering process:

- Use of SnAgCu alloy or matt pure tin as the solder; or:
- Addition of anti-whisker additives; or:
- Tempering of the populated PCB for one hour at 150 °C (consideration must be given to the suitability of the components for this treatment)

Assembly:

- Mounting of the components on the PCB mechanically unstressed
- Installation of the PCB mechanically unstressed

4 Additional measures for the detection of tin whiskers

Traces with non-isolated surfaces, connected to positive or negative voltage and thus intended to bring about the safe state in the event of a short-circuit, can be situated around the solder points of safety-related current paths. However, this measure detects only short-circuits between traces, and cannot cover the complete current path including the component terminals.

5 Consideration in quantification

The probability of a dangerous failure per hour is calculated for safety functions (PFH or SIL). This takes account of the probability of a dangerous failure of any component involved, including the PCB. At present however, no figures are available describing the probability of the incidence of tin whiskers; nor is any method known as yet by which the high number of possible short-circuits caused by whiskers and their different effects upon the electronic circuit of the safety function can be analysed with justifiable effort. Quantitative analysis of dangerous failures of safety functions caused by tin whiskers is therefore as yet not possible.

6 Literature

[1] NASA goddard tin whisker homepage (http://nepp.nasa.gov/whisker)

[2] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. OJ EU (2011) No. L 174, pp. 88-110
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:174:0088:0110:EN:PDF

[3] Method for evaluation of short-circuits caused by whiskers on PCBs and on electrical fuses. IFA-Project 5104

[4] EN ISO 13849-2: Safety of machinery – Safety-related parts of control systems – Part 2: Validation (02.13). Beuth, Berlin 2013

[5] EN IEC 61800-5-2 (VDE 0160-150-2): Adjustable speed electrical power drive systems – Part 5-2: Safety requirements – Functional (04.08). Beuth, Berlin 2008

[6] EN 60664-3: Insulation coordination for equipment within low-voltage systems – Part 3: Use of coating, potting or moulding for protection against pollution (03.03, current version 10.10). Beuth, Berlin 2010