# An Electrical Characterization of Tin Whisker Shorting

Robert D. Hilty[1] and Ned Corman
Tyco Electronics, Harrisburg, PA, USA.

**ABSTRACT:**

Tin whiskers are one of the greatest reliability concerns with lead free electronics. The blueprint for failure is simple – a metallic filament of tin bridges between two conductors and leads to an electrical short. While this makes intuitive sense, there are limits to when this failure mechanism will be active. This research examines the role of tin oxides on preventing electrical conduction between tin whiskers and an adjacent contact. Contact resistance measurements were made to tin whiskers under various loading schema to evaluate the conditions under which whiskers would lead to electrical conduction. Electrical conductivity to the whiskers requires breakdown of inherent oxide layers present on tin; this can be achieved mechanically or by way of electrical breakdown. Electrical breakdown voltages of 3 volts or more were required to achieve continuity.

## Introduction

Tin whiskers can cause electrical short circuits. Few engineers will debate such a simple statement. However, the conditions under which a whisker will cause a short are only partially understood. Tin whiskers most often cause glitches in the electronics when the current between the conductors is greater than the fusing current of the whisker. The fusing current of whiskers is typically around 5mA.[2] This is a temporary interruption in the circuit. Longer term shorts result either from stable interconnects at low amperages or metal vapor arcing. Meal vapor arcing occurs in low vacuum settings where a plasma can be created.[3]

Tin whisker failures have been reported which lead to system malfunctions and it is clear that whiskers can form a long term stable conduction path.[4] If you take the simplest approach of computing the resistance of a tin whisker based on geometry, you can model it as a cylinder with a length of 200μm and a diameter of 2μm and a bulk resistivity, ρ, of 110 nΩ•m.

$$R = \frac{\rho L}{A} \approx 7\Omega$$

In our lab we have been able to produce whisker shorts across terminals. The short circuits result in a resistance typically on the order of 100 **Ω**. Thus, some fraction of the resistance is a result of the electrical constriction resistance of the contact interface and the balance is the bulk resistance.

If designing a tin-to-tin electromechanical contact interface, there are some well known guidelines we can follow to ensure a reliable contact.[5] An applicable guideline is that tin plated contacts require at least 100 grams (0.1 N) of normal force in order to create a low and stable contact resistance. This requirement helps overcome the ubiquitous tin oxides that coat the tin plated surfaces. The relatively soft tin plating yields under pressure, cracking the brittle superficial oxide layers. This produces oxide free, metal-to-metal interfaces during mating. The required forces for mating to gold, which does not normally form an oxide, are orders of magnitude lower to achieve a stable resistance.

To investigate the performance of tin plating at very low forces and stresses, we prepared some tin plated samples to measure contact resistance. Tin oxide grows rapidly at room temperature. However, to simulate an oxidized surface that exists after aging for longer times, the parts were artificially aged at 50 C for about 65 hours. The contact mating device was a narrow cylinder with a radius of 0.5mm (like a coin sitting on its edge) stamped from a 0.2mm thick sheet of phosphor bronze, then plated. Using a contact resistance probe and dry circuit test conditions (50mA maximum and 50mV maximum), each contact was brought into contact with the flat surface with a monotonically increasing load and no lateral translation. The load was varied from 0.5 g ($5.0\times10^{-4}$ N) to 30g ($3.0\times10^{-2}$ N) while measuring contact resistance. The test was replicated 9 times to provide an indication of the statistical repeatability of the results. The resulting contact resistance curves are plotted on a log-log scale as shown in Figure 1.

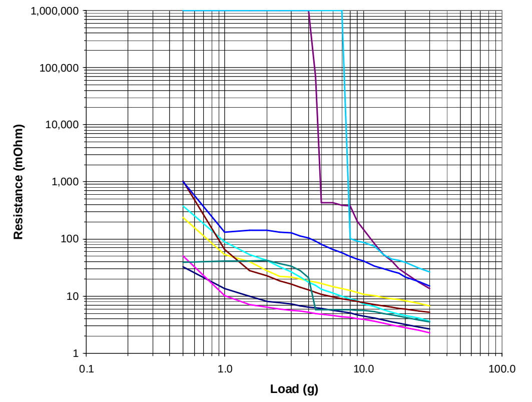

Figure 1. Contact resistance plot showing the resistance in milliohms versus the mating force in grams for tin plating mated to tin plating.

The contact resistance data shows that the nominal contact resistance, as well as the variation in the measured resistance, decreases as the mating load is increased. As the load is increased, the mating interfaces deform to promote intimate metal-to-metal contact and less restricted current flow. However, at low applied forces the resistance increases exponentially as the load is reduced. For two of the test conditions, the localized oxide layer was not penetrated sufficiently to provide electrical continuity until the applied normal force was increased beyond 4 and 7g. At this point, the deformation became sufficient to deform the oxide layer enough to establish continuity.

If a whisker grows from one surface to another, will it create a short? This may depend on the mating forces at the contact interface.

Fukuda and Osterman[6] examined the potential for whiskers shorting after they break off of the surface on which they are growing. In this work, whiskers were harvested from tin plated samples, then sprinkled onto the surface of a adjacent conductors. While whiskers were seen to be bridging across the electrodes, continuity could not be achieved through the whisker. In this case, the applied normal force is only the force due to gravity and thus is very low since the mass of a whisker is very low.

Mei examined the likelihood for whiskers breaking from a tin plated surface and found that the likelihood was very small.[7] He examined tin whiskers exposed to shock, vibration and wind tunnel environments. These results suggest that whiskers are not very likely to break off; further, if they do break off, they may not be a suitable electrical conductor due to the low applied normal forces and dielectric oxide coatings.

## FEM Analysis and Contact Physics

A whisker is a long slender body. For this analysis, we will select a whisker that is a needle shape and which grows normal to the surface of the plating. The whisker was modeled as a cylinder that is 100 μm long and 2 μm in diameter with an elastic modulus of 50 GPa. This is a severe case in that the whisker is still relatively short and stiff, thus it will produce a relatively large applied normal force at the contact interface. The whisker is loaded normal to the plated surface to an axial displacement of 10 μm. In order to simplify the computation, the whisker is pre-deflected in the direction perpendicular to loading direction in order to remove buckling considerations (in essence, we have pre-buckled the whisker). These displacements were varied from 1 to 10 μm to gauge the effect on the approximation.

Figure 2 shows the results of the FEM analysis. Contact forces are exponential with displacement due to the bending stiffness of the whisker. The normal forces on the tip of the whisker vary from $6 \times 10^{-6}$ to $1 \times 10^{-5}$ N at the deflection of 10 μm.

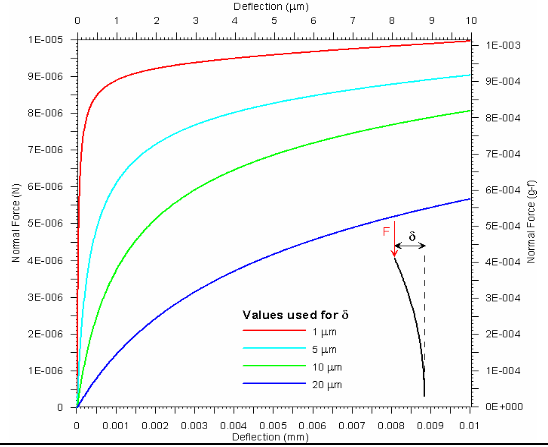

Figure 2. FEM predictions of the normal force applied between a tin whisker and the mating interface as the whisker bends to accommodate the displacement.

The highest load we compute in this analysis is 500 times smaller than the lowest load we could apply in our contact resistance test and 10,000 times lower than the recommended contact normal force for a stable electrical contact interface. Based on this very low force, it is difficult to exactly predict the contact resistance values we would experience in the force regime of a tin whisker. However, we can extrapolate the contact resistance data available to the forces we expect from a whisker. The upper bound of this analysis predicts open circuit contact resistance. The lower bound analysis predicts a contact resistance of 100 ohms.

The resistance values predicted for mating to tin are high due to the presence of the dielectric tin oxide layer on the surface. Other contact metallurgies, such as electrodeposited gold, do not form oxides under normal conditions. As a comparison, we examined the contact resistance of electrodeposited cobalt hardened gold mated to a PCB coated with ENiG( electroless nickel immersion gold). The applied force range was the same as the tin samples, 0.5 to 30 g. Figure 3 shows the results of 19 replicate samples. The results are quite stable and show the repeatable performance of a gold finish.

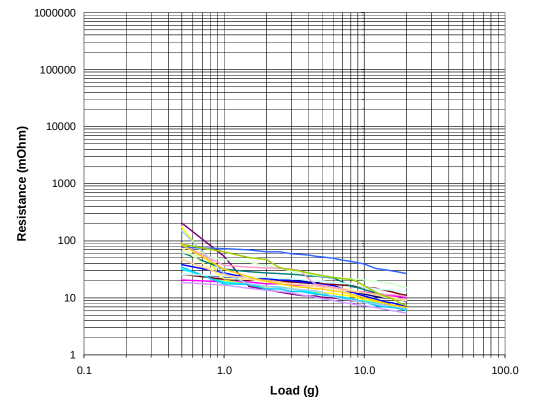

Figure 3. Contact resistance plot showing the contact resistance versus the applied normal force for gold electroplating contacting ENiG.

If we perform a similar extrapolation analysis of the contact resistance of gold, using the force regime of mating to a tin whisker, we get an approximate contact resistance of 1 ohm for the clean gold surfaces.

## Materials for Whisker Samples

Tin whisker samples were created by electrodepositing nominally 3 µm of matte tin using a commercially available tin sulfate plating bath. This bath has been used previously to grow tin whiskers and employs no specific tin whisker counter measures.[8] The base metal is C26000 brass (CuZn30) and was prepared for plating with a 10 second electroclean in 10%sodium hydroxide and an acid etch (10% sulfuric acid) for 10 seconds. Samples were stored at room ambient conditions to allow whisker growth. A copper electrode was also coated with nickel and tin plating (3 µm thick), which was free of whiskers.

In some experiments, the tin platings and or whiskers were coated with gold. The coating is vapor deposited pure gold using sputtering to a typical thickness of 10nm.

A small study was also performed on zinc whiskers. The zinc whiskers were 100 µm long or greater and were grown at room temperature on an electroplated zinc layer over steel.

## Methods

All electrical contact measurements were made with a Keithley 580 micro-ohm meter. None of the measurements were at dry circuit conditions since continuity could not be established under these regimes. On the 20 kΩ scale, the instrument has a 1 ohm resolution, delivers 10 µA current maximum and has an open circuit voltage of 1 volt maximum. On the 2 kΩ scale, the instrument has a 100 mΩ resolution, delivers 1 mA current maximum and has an open circuit voltage of 1 volt maximum.

In order to probe the whiskers to examine the contact resistance, samples with sufficiently long whiskers were fixed in a vise attached to a 3 degree of freedom micrometer base. A contact probe was configured for a four wire contact resistance measurement and the probe had an adjustment for the probe tip position. The probe was brought into contact with the whisker, deflecting the whisker to approximately 10um. The system is observed under an optical microscope to facilitate the contact.

## Results

We know that tin whiskers can cause electrical short circuits. NASA has reported tin whisker failures that have persistent and stable continuity between electrodes. In our own studies, we have seen whiskers produce electrical shorts that vary in resistance from 100 ohms to several kilohms.

However, dry circuit continuity measurements unexpectedly showed that touching a tin plated probe to a tin whisker did not generally result in electrical continuity. Tests were repeated on dozens of samples and showed a consistent response. Figure 4 shows and example of the whisker contact configuration. The top image displays the contact probe and a long whisker (500 μm) growing normal to the tin plated surface. The bottom image shows the probe mechanically mated to the whisker. The whisker can be seen in the deflected state. If the probe is removed from the whisker at this point, the whisker springs back elastically to its original position.

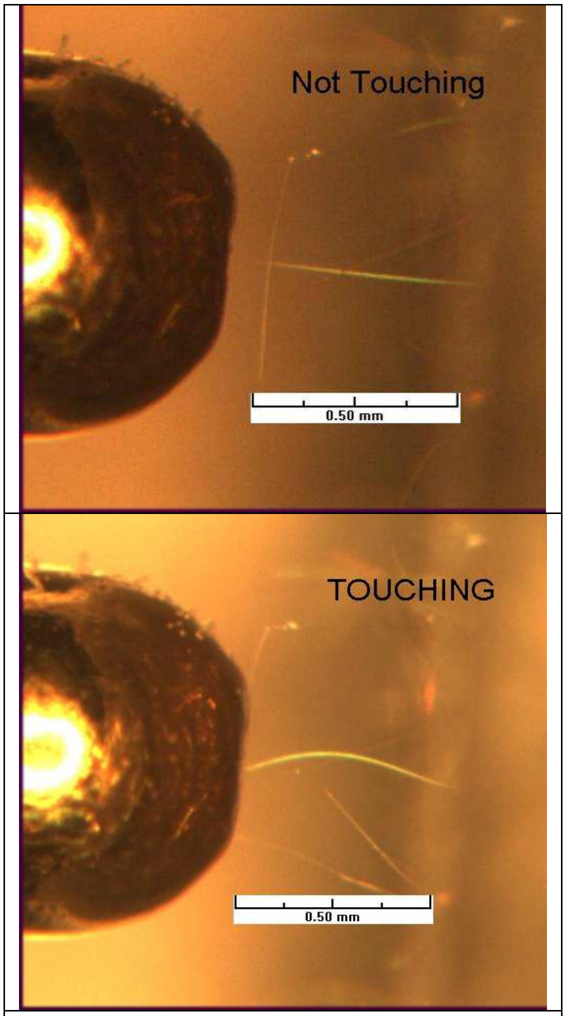

Figure 4. Micrographs of tin whisker being contacted by electrical resistance probe. Top image shows whisker prior to contact. Bottom image shows whisker compressed by the probe. Under compression, this whisker did not exhibit continuity.

We hypothesized that the oxide surface was impacting the ability to develop continuity. We introduced a mechanical disturbance by striking the table near the whisker fixture to induce a mechanical shock. This produced visible vibration of the tin whisker, but no long term continuity; however we sometimes observed short term (milliseconds) continuity. This effect was not repeatable and the resistance values were not recorded.

To eliminate the effect of the oxide layer, samples with tin whiskers were coated with a thin layer of Au then mated to ENiG finished surfaces. Figure 5 shows the first of several efforts to mechanically mate to a gold coated tin whisker. This sample developed continuity under compression with a measured resistance of 846 ohms. Based on the geometry of these whiskers, the bulk resistance of the whisker is expected to be 5 to 15 ohms, with the remainder of the 846 ohms measured being the contact resistance and any current tunneling effects in the substrates. Additional experiments on other whiskers generated measured resistances in the range of 600 to 1000 ohms.

Figure 5. Tin whisker coated with gold and mated to ENiG finished surface. The whisker developed continuity under compression with a measured resistance of 846 ohms.

It was discovered that sporadic continuity could be established by increasing the measurement voltage above 3 volts. In some cases, increasing the voltage to as high as 50 volts did not result in breakdown of the oxide with concomitant development of continuity. For those tests, the current was limited to less than 1 mA, so that if breakdown did occur, the current would be insufficient to destroy the whisker. To quantify this effect, we measured the current flow as the voltage sweeps from 0 to 20 volts or more while the whisker was under compression contact.

Figure 6 shows a typical plot of the current flow across a tin whisker when it is mated to a tin plating as the voltage is gradually increased. As the voltage increases, a breakdown voltage is reached and the whisker becomes electrically conductive. In this case, the conductivity of the whisker is brief and is not stable.

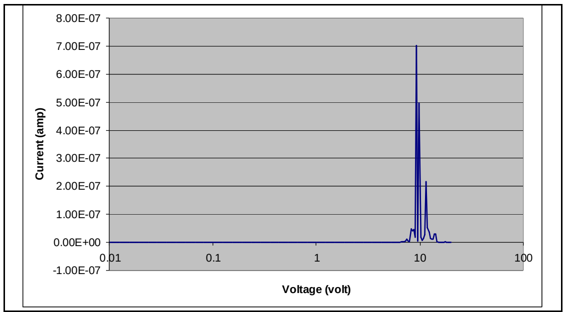

Figure 6. Plot of current flow as the voltage is increased across the contact of a tin whisker mated to a tin plating.

At a maximum voltage of 20 V, the whisker shown above was not electrically stable. The test was halted, then re-run starting at 0 volts. Figure 7 shows the second voltage sweep, which shows no breakdown and hence no continuity.

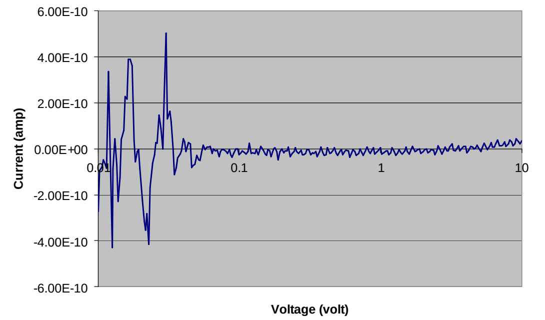

Figure 7. A second voltage sweep of the same whisker shown in the figure above. This time, we see no voltage breakdown and the whisker is not electrically conductive.

The cause for the change in breakdown is unclear. To be certain that the whisker had not fractured, the contact probe was retracted from the whisker. Elastic strain energy in the whisker was released and the whisker became straight again. The probe was re-applied and the voltage sweep performed again. The results are shown below in Figure 8. Again, we see a voltage breakdown as we sweep up to 7 volts and again, the continuity is unstable.

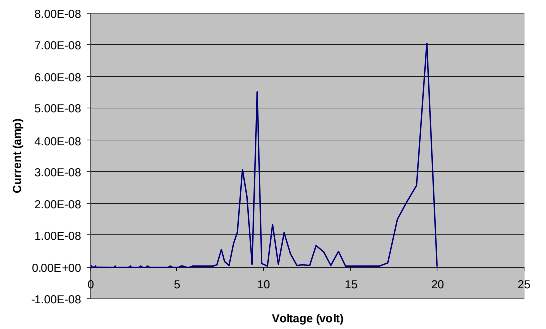

Figure 8. A third voltage sweep on the same whisker after the tool had been retracted, then re-applied. This time the voltage breakdown occurs at about 7 volts.

These experiments were repeated dozens of times to determine the typical voltage breakdown values. In some cases, the electrical contact is intermittent and in other cases, as shown below in Figure 9, the electrical continuity is quite stable. In this test, the current was limited at 1 mA. In about 1/3 of the cases, voltage sweeps were unable to establish continuity. In the balance of tests, the electrical breakdown occurred at voltages between 3 and 26 volts.

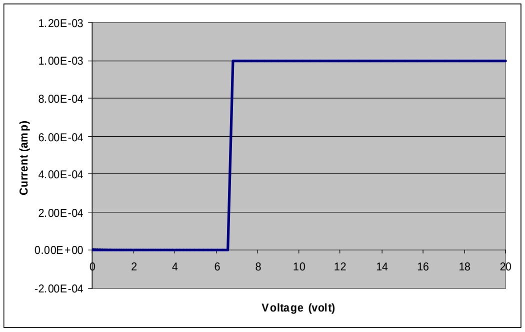

Figure 9. Voltage breakdown of a tin whisker mated to tin plating as the voltage is increased to 20 V. The whisker establishes stable electrical contact at 1mA of current.

An unexpected observation during these experiments was the fracture mode of the whiskers. Whiskers are quite elastic and the compression levels applied here are not expected to lead to fracture of the whiskers. During the testing we found that the whiskers almost always fractured at the root of the whiskers and became attached to the electric probe. It is likely that the stress in the whisker is highest at the root since the shape often mimics a simple cantilevered beam. Further, the breakdown of the oxide layer at the contact interface during the voltage sweep produces clean tin surfaces which readily weld together. Figure 10 shows a tin whisker during the voltage sweep and the whisker welded to the electrical probe after the test.

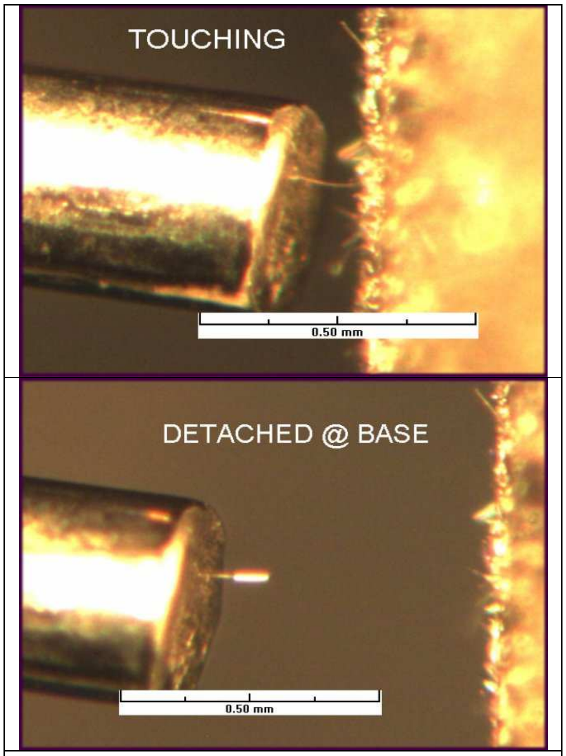

Figure 10. Whiskers start out growing from the tin surface. After mating and electrical activation, the whiskers fracture at or near the whisker root and adhere to the test probe.

The whiskers do not make electrical continuity immediately when touched. It may be that exposure to time and or temperature may have an impact on the continuity.

A tin whisker was contacted to the tin plated probe and held in position. Voltage sweeps were made on the connection up to a voltage of 2V over a period of 46 hours. The whisker never established continuity. After 46 hours, a voltage sweep up to 20 volts led to voltage breakdown at 15 volts, which caused the whisker to fuse open. Another whisker was tested to 96 hours, after which it did not show continuity until the voltage sweep when it demonstrated breakdown at 7 volts.

Since temperature accelerates the diffusion process, we configured the test to apply heat to the coupon with the tin whiskers on it during the test. The coupon was heated to about 50 C and the tin whisker was mated to the electrical probe. The parts set at temperature for about 1 hour and did not have electrical continuity until the voltage sweep reached sufficient voltage to breakdown. This test was relatively short – a longer test requires a more sophisticated test configuration than was available for this work.

Some investigations have been made regarding the potential similarities between tin whiskers and other metal whiskers.[9] We obtained a sample of a steel washer that had been electroplated with zinc and was growing zinc whiskers. The whiskers were >100µm long. We performed similar contact experiments to the zinc whisker to determine if electrical contact could be made. Mechanical mating to the zinc whisker did not produce electrical continuity. We made no attempt to determine the voltage breakdown levels in zinc whiskers, but we would expect the same process to occur in zinc.

## Discussion

This work is based on the premise that the tin oxide layer that covers both the tin plated electrical probe and the whisker itself leads to an insulating layer. This layer prevents electrical contact and is normally disturbed by mechanical forces when used in contact interface applications. Since the force is very small on a tin whisker, the force is too small to provide disruption of the oxide layer. Slade and Taylor[10] provide a summary of the breakdown voltage potential and phenomenon for very small gaps in ideal (clean and polished) conditions. They evaluated published data for breakdown in gaps between 0.2µm and 40µm in air and in a vacuum. For gaps below 4µm, in air and in a vacuum, there is a linear relationship between gap length and voltage. Data suggests that the relationship in air lies between 65v/µm and 110v/µm. For the breakdown voltages we see in this work, 3 to 26 volts, this theory predicts a minimum spacing of 30 to 260nm between the whisker and mating interface.

Figure 11 shows some limited data on the growth rate of tin oxide on tin/lead solder.[11] This is also the growth rate at room temperature. This data suggests that the oxide thicknesses on our whiskers and the mating contact probe are likely in the thickness regime of 150nm. Our configuration is a contact interface with oxidation on both surfaces, thus the oxide thickness combined is about 300nm. This is only slightly thicker than the high end of what was predicted using the data of Slade. However, this is a rudimentary analysis that fails to take into account the voltage breakdown rates in tin oxide (instead of air) and the impact of localized fracturing and inhomogeneity of the tin oxide layer in the region of the contact interface.

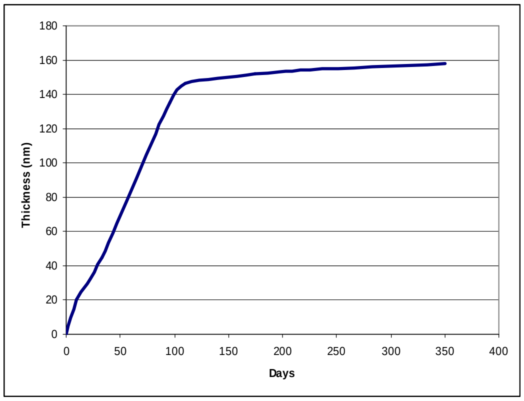

Figure 11. Tin oxide growth rate in tin/lead solder at room temperature.

In our own experiments with tin whiskers, we have seen whisker shorts between adjacent conductors. In some cases, the sample history is not completely known. In some cases, the parts have already been exposed to voltage differentials while others have not seen any electrical activation. Yet, both of these whiskers show continuity. An unknown mechanism is providing diffusion at the contact interface or oxide displacement, which allows for continuity. However, it is clear that in many cases, the application of voltages greater than 3 volts is sufficient to cause voltage breakdown and the establishment of continuity though a tin whisker.

## Conclusions

1. Mechanically contacting a tin whisker is insufficient to establish electrical continuity between the whisker and an adjacent electrical probe. This is proposed to be the result of tin oxide formation on the surface of the whisker and the mating interface which retards electrical conduction. A similar effect was observed when mating to a zinc whisker.
2. FEM analysis predicts that the contact forces generated by tin whiskers under compression is about 1mN, which is 10,000 times lower than required to establish a stable electro-mechanical interconnect.
3. Electrical continuity can be established in a tin whisker if a voltage is applied to the contact interface. In this work, the voltage required varied between 3 and 26 volts.
4. Tin whiskers fuse open easily under the action of 7 to 15mA. This is dependent upon the geometry of the whisker.
5. Continuity could not be established to a tin whisker after mating for time periods up to 96 hours or short time elevated temperature exposures.

## Acknowledgements

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