Enhancements to Current Tin Whisker Risk Assessment Methods

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Abstract

The author published an application-specific tin whisker risk assessment algorithm in 2003, and issued an updated version in 2004. This algorithm is currently being used by a variety of high reliability manufacturers to manage the risks posed by tin whisker induced failures. Other similar methods have been developed elsewhere and are also being used. During the past year experimental data has become available on the performance of conformal coating for containing tin whiskers. Additionally, data and a model have been published concerning the distribution of tin whisker lengths.

This paper outlines the incorporation of this new understanding into improved risk assessment methodologies. A model is presented that can be used to quantify the mitigation provided by imperfect conformal coating. Differences in the results predicted by the current and proposed improved methodologies, and their implications are discussed.

Background

Manufacturers of high reliability electronics must manage the risks associated with tin whiskers, while continuing to meet other important customer-driven requirements such as performance, cost, and delivery schedule. Standardized approaches for managing these trades are in use in the industry and have been embodied in the new standard GEIA-STD-0005-2, which is currently out for balloting. A documented process for performing detailed risk assessments is required for compliance to the standard, and also to satisfy the concerns of the customer base.

A risk assessment algorithm tool has been developed to provide a standardized method for performing application-specific tin whisker risk assessments. The details of the latest revision of this tool (Revision B) have been described previously [1,2]. In the year and a half between the release of the latest revision of the tool and today there have been significant editions to the knowledge base regarding the behavior of tin whiskers. Therefore, the opportunity now exists to incorporate this improved understanding into a new revision of the tool that will provide more realistic answers, backed up by real data. Other investigators are developing standardized risk assessment methods should also account for these recent developments. This paper describes some of the critical advances in tin whisker knowledge, in the two important areas of whisker length distribution and the ability of conformal coat to mitigate against whisker shorts. Also discussed is how this knowledge should be incorporated into risk assessment methodologies.

Risk assessment tool basics

It is intended that the standard risk assessment tool be usable by design engineers and component engineers who are not experts in the tin whisker phenomenon. Therefore, input data for use of the tool must be restricted to information that can reasonably be expected to be available to these users. Detailed information on plating process parameters, states of stress in the coating, crystal orientation, etc. are therefore not included.

The tool must also be user-friendly and provide clear numerical answers. These features are necessary to insure that a standard process can be performed at a wide variety of locations.

The tool has been constructed in such a way that the recommendations that it provides are generally considered to be conservative. Conservative in this context implies that the beneficial effects of any particular mitigation will be underestimated. This will then drive decision-makers to be more likely to employ too much rather than too little mitigation for the intended application. This feature is critical in gaining customers confidence in the results provided by the tool.

The current and previous revisions of the tool have been developed with the above requirements in mind. These requirements affect how data will be used during the development of the next revision of the tool. In particular, when estimating the effects of a particular mitigation the goal is not to be as accurate as possible in predicting the exact degree of mitigation, but rather to make a prediction that will almost certainly underestimate the amount of mitigation provided.

The risk assessment tool has twelve inputs (r_1 through r_{12}). It is very desirable to retain the same twelve factors for the future revisions of the tool. This will permit continuity in the processes for collecting data, and will also permit easy reassessment of risks that have been previously analyzed. How each of these factors is arrived at, and how the factors are combined mathematically may be altered as necessary without compromising the utility of the revision.

Conductor Spacing

The spacing between the tin plated surface under evaluation and the nearest non-coated conductor that could be at a different electrical potential is the first factor used by the risk assessment tool. Conductor spacing affects the risk of tin whisker shorts because only whiskers longer than the conductor spacing can physically bridge the gap. Any collection of actual whiskers will contain whiskers of various lengths between zero and some maximum value. Therefore, the risk of tin whisker shorts will always decrease as conductor spacing increases.

The possibility that a whisker will bridge a gap also depends upon the orientation of the whisker. A whisker whose length is exactly equal to the gap size can only bridge the gap if it is perfectly aligned. As the whisker length grows longer than the gap the solid angle over which a whisker could bridge grows. However, the orientation of long whiskers can vary. To demonstrate this effect a brass rod that was plated with bright tin that had grown lengthy whiskers after several years was examined. The location and orientation of several long whiskers was documented. The rod was then subjected to 100 thermal cycles between -40°C and plus 71°C, and was re-examined. Several of the long whiskers were clearly identified as having rotated through very large angles about their bases. This effect is shown in Figures 1 and 2.

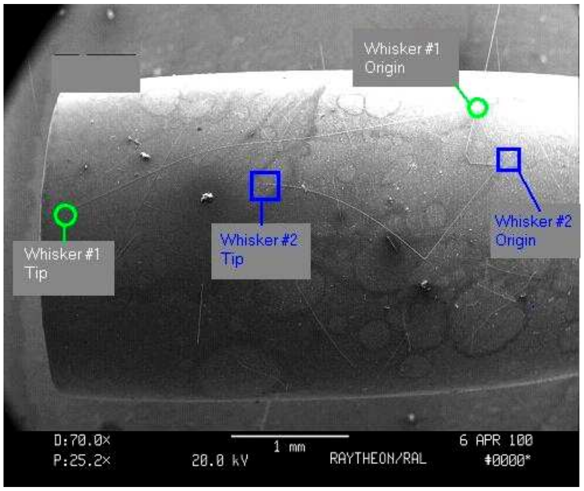


Figure 1. Orientation of two long whiskers prior to thermal cycling.

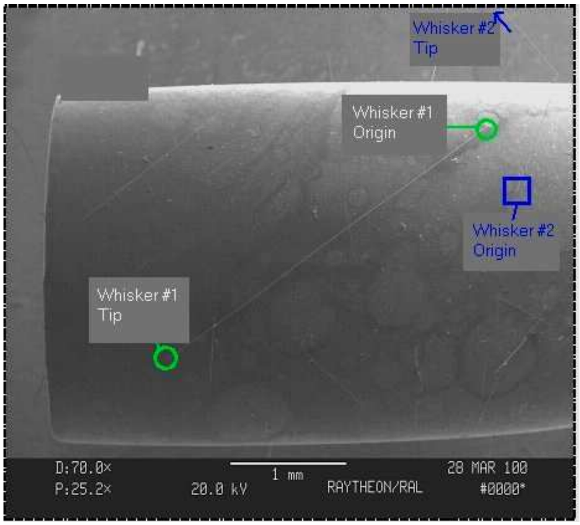


Figure 2. Orientation of the same two long whiskers following thermal cycling.

Therefore, the fact that a whisker may be oriented in a direction that does not result in a failure at one particular time does not assure that this whisker will remain oriented thusly in any future time. The conservative approach, therefore used to assume that all whiskers with a length greater than the gap spacing are equally probable of producing a failure. This overstates the risk and thereby underestimates the mitigation provided by increasing gap size.

Let us therefore assume that the risk of a short across a given gap is proportional to the number of whiskers of sufficient length. In this case, the risk as a function of gap size can be derived directly from the probability distribution of whisker lengths. The risk of failure for a specific gap size will be proportional to the integral of the probability density from that length to infinity. In statistical parlance, this function is referred to (ironically in this case) as the Survival Function S(x). The degree of mitigation provided by increasing the gap size from length x_1 to length x_2 is given by: $S(x_1)/S(x_2)$. At the time when revision B. of the algorithm was developed, there was insufficient published data to provide this probability distribution, so a conservative guess was made for the degree of mitigation.

Fortunately, the results of recent work by Hilty and Corman [3] and by Fang, Osterman and Pecht [4] are now available to fill this void. Both investigations indicate that the probability density decreases strongly with length. Fang, Osterman, and Pecht fit their data to a log-normal distribution. Hilty and Corman use Johnson transformations to obtain good fits. Both investigations then utilize Monte Carlo techniques to predict failure rates for specific geometric assumptions. The Monte Carlo techniques employed accounts for whisker orientation, so the results of this analysis may not be sufficiently conservative for direct incorporation into the risk assessment tool. Fang, Osterman, and Pecht account for different probabilities associated with different orientations, so this approach is a bit more conservative.

Hilty and Corman have generously agreed to share their raw data with me. They performed whisker density and whisker length measurements on two different platings systems. One of the systems was formulated to grow a high density of whiskers with a relatively high quantity of long whiskers. Since it is these longer whiskers that are of greatest interest for risk assessments I have confined my analysis to this data set. My goal in reviewing these data is to check the validity of the results that have been provided by Revision B of the risk assessment algorithm.

Whisker length measurements from Hilty and Corman are plotted in Figure 3.The y-axis indicates the percentage of whiskers that are greater than or equal to a given length, which is S(x). Logarithmic scales are used for both x and y axes to better display the distribution of longer whiskers.

For the portion of the distribution greater than 250 μ in length I have fit the data to the line indicated on Figure 3. This line will be used to extrapolate the results to longer whisker lengths that are contained in the data set. Hilty and Corman fit their data using a Johnson Transformation that predicts a lower occurrence of longer whiskers then would be predicted by my simple linear fit. Therefore, my simplified fit will provide a more conservative estimate of the mitigating affects of conductor spacing.

Data over the range between 50 and 250 μ in length are plotted in Figure 4 on a semi-log scale. Again, I have used a simple linear fit to the data to estimate the value of S(x) over this range.

Using the estimation for S(x) for x> 250 μ the reduction of whisker risk obtained by increasing the conductor spacing beyond 250 μ can be calculated. This result is plotted in Figure 5, normalized to the risk and 250 μ. Also plotted is the factor specified in Revision B of the risk assessment tool. It can be seen that the mitigation predicted by the new calculation is greater than the mitigation that was assumed by the prior revision of the tool. This is good news, because it implies that previous risk assessments have been conservative, and that the new revision can safely assign a greater degree of mitigation for this particular factor.

In Figure 6 the combined results for the range between 50 and 1000 μ together with the Revision B factor are plotted. It can be seen that for gap sizes below about 200 μ that the new, calculated risk is higher than the old factor would indicate. This is a warning that the current Revision of the tool does not adequately account for risks posed by very small gap size. Thankfully, gap sizes below 50 μ are uncommon on existing high-reliability electronic assemblies. However, extremely fine pitch geometries may become more prevalent in the future so it is important to amend our risk assessment procedures accordingly.

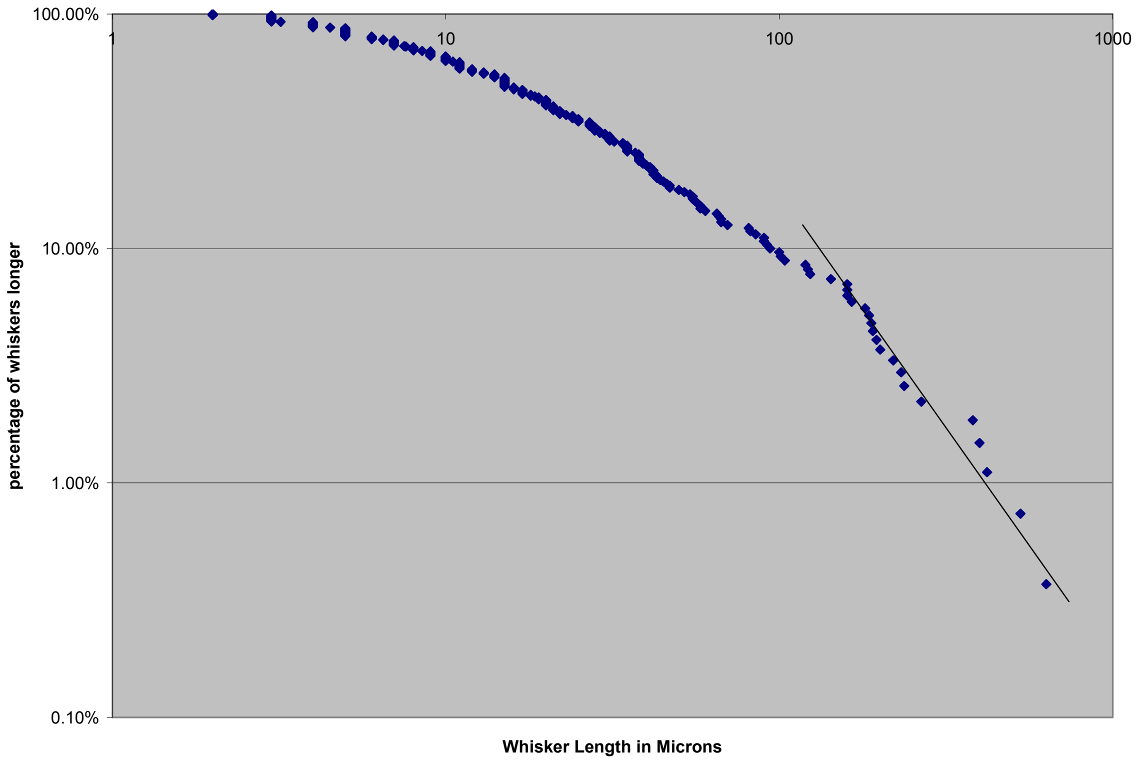


Figure 3. Whisker length data from Hilty and Corman plotted on a log-log scale.

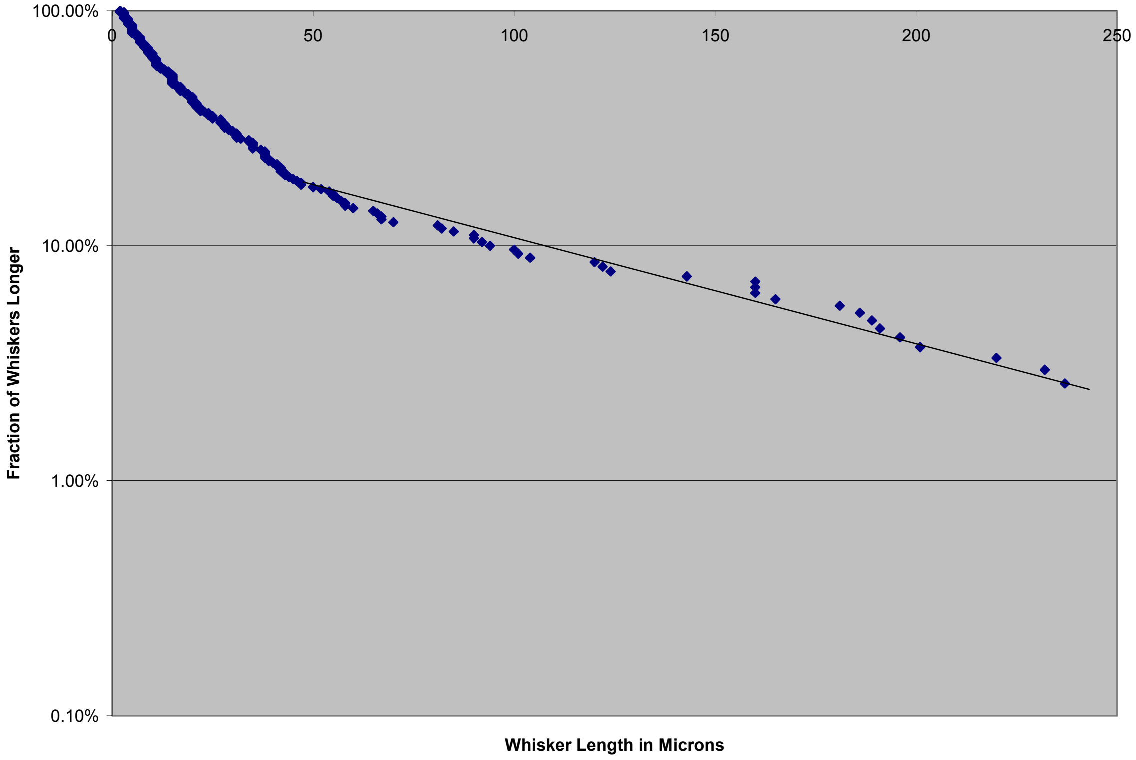


Figure 4. Whisker length data from Hilty and Corman plotted on a semi-log scale.

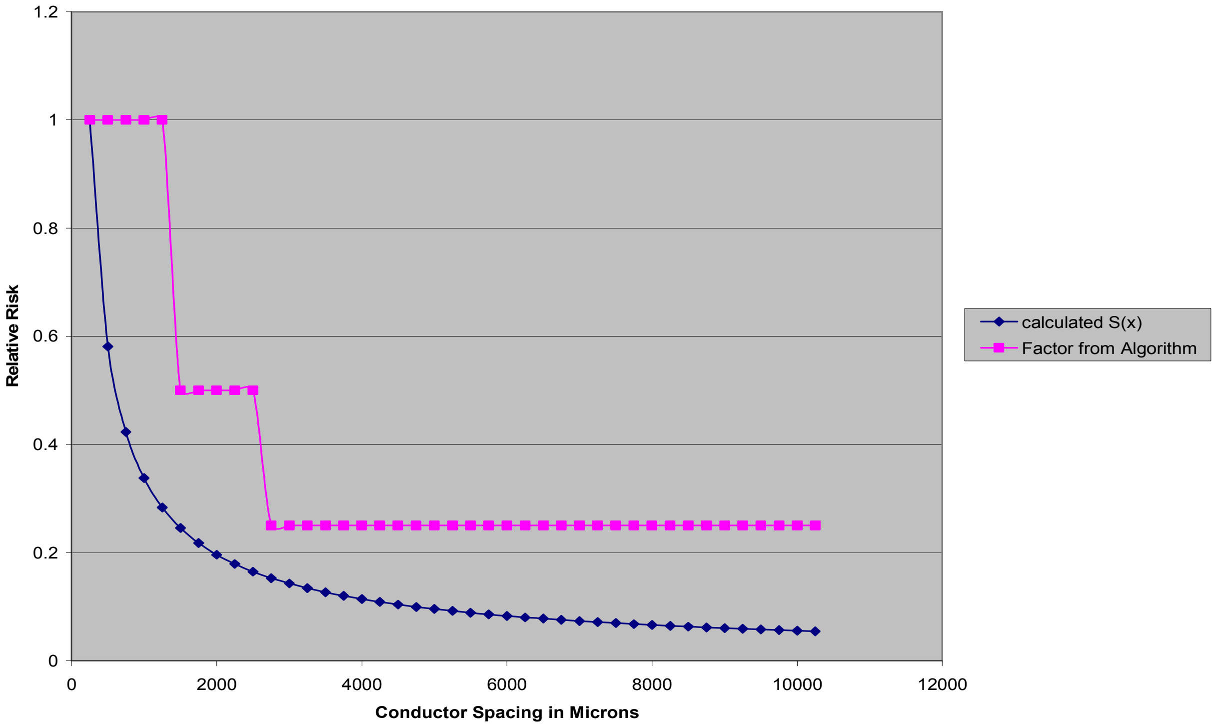


Figure 5. The degree of mitigation provided by increasing gap size from 250 µ to beyond 1 cm (normalized to the value adds 250 µ) as estimated from whisker length data, and compared with the value assumed in Revision B of the standard risk assessment tool.

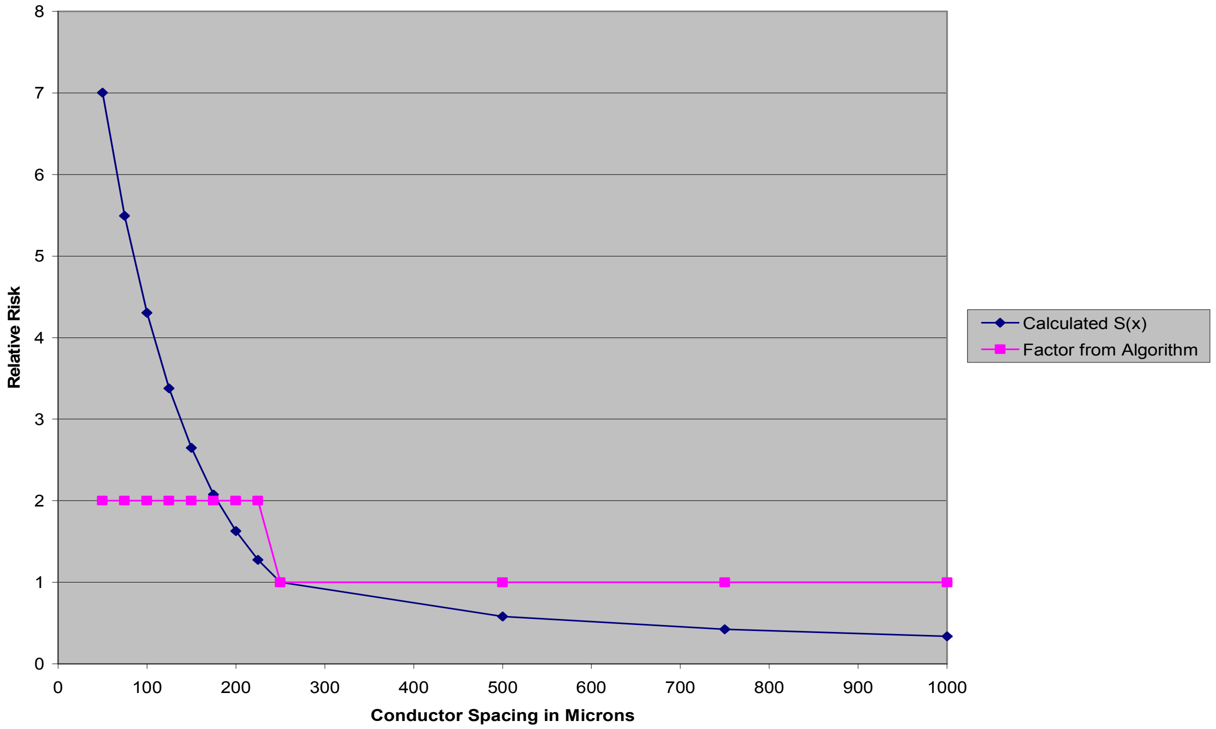


Figure 6. The degree of mitigation provided by increasing gap size from 50 µ to 1 mm (normalized to the value adds 250 µ) as estimated from whisker length data, and compared with the value assumed in Revision B of the standard risk assessment tool.

Fang, Osterman, and Pecht have used a log-normal distribution to fit their whisker length data. This approach permits the use of closed-form mathematical analysis rather than only numerical approaches. The survival function associated with a log normal probability distribution is given by:

$$S(x) = \tfrac{1}{2}\left[1 - erf\left(\frac{\ln x - m}{s\sqrt{2}}\right)\right] \quad \text{Equation 1}$$

Where:
erf is the "Error Function"

and the values of m and s are related to the mean and standard deviation by:

$$m = \ln\left(\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right) \quad \text{Equation 2}$$

and

$$s = \sqrt{\ln\left(\sigma/\mu\right)^2 + 1} \quad \text{Equation 3}$$

Improved risk assessment algorithms should incorporate the use of S(x) based upon actual whisker length data. The user will only need to input gap size in either microns or mils, and the tool will calculate the appropriate mitigation factor.

Conformal Coating

A study was performed by NASA several years ago that indicated that some level of tin whisker risk mitigation was provided by the use of a particular urethane conformal coat.[5,6,7] In addition, an analysis was performed that indicated that tin whiskers that pass through open space between two conductors should not be capable of penetrating conformal coat on the distant conductor, but instead would buckle prior to penetration.

The buckling phenomena predicted by Leidecker and Kadish [5] have been observed in our laboratory. In this case the whisker was seen to have buckled after contacting a very soft silicone potting material. Penetration of the whisker tip into the silicone was so infinitesimal that the buried tip of the whisker was still observable using the scanning electron microscope. These images are shown in Figures 7 and 8.

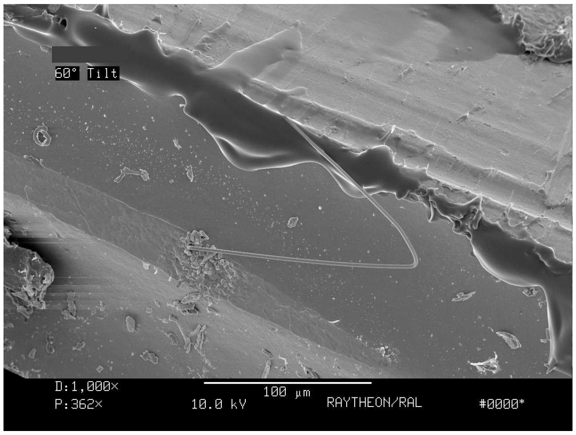


Figure 7. A long tin whisker which buckled when it continued to grow after contacting silicone potting material at its tip.

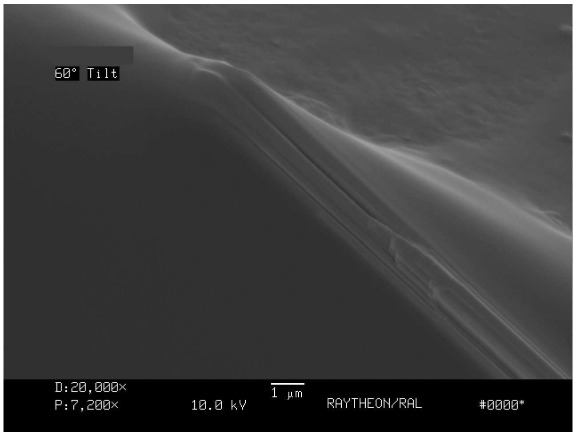


Figure 8. Tip of whisker shown in Figure 6 above. Penetration into the soft silicone is negligible.

Conformal coat has been counted upon to provide significant levels of tin whisker risk mitigation by many manufacturers of high reliability electronics.

A larger study of the ability of conformal coating to contain tin whiskers was published by Woodrow and Ledbury [8]. This study demonstrated that tin whiskers have the ability to penetrate conformal coating. In addition, it was shown that whiskers can also grow laterally beneath the coating. These results have prompted a reassessment of the mitigating capability of conformal coat.

Meaningful risk assessments must take into account the performance of actual coating systems and actual circuit geometries. Assumptions of perfect coating performance will result in overly optimistic risk assessments. On the other hand, excessive concern regarding whisker growth mechanisms that cannot result in electrical shorts will result in overly pessimistic risk assessments. It is important to be mindful of the fact that conformal coating (like other strategies) only provides mitigation against whisker-induced failures, and not 100% prevention. What needs to be assessed is how much mitigation a particular real coating system will provide in actual circuit applications.

Conformal coat that is applied to real circuits will result in variable coating thickness, with some isolated areas exhibiting zero thickness (void). The effect of coating voids must be considered as void areas will be completely unmitigated.

Although Woodrow and Ledbury's [8] data indicates that whiskers can penetrate conformal coating, it also shows that the number of whiskers that penetrate a coated surface is only a fraction of the number of whiskers that grow on a similar uncoated surface. This effect is shown in Figure 9 reproduced from Reference 7 (with permission).

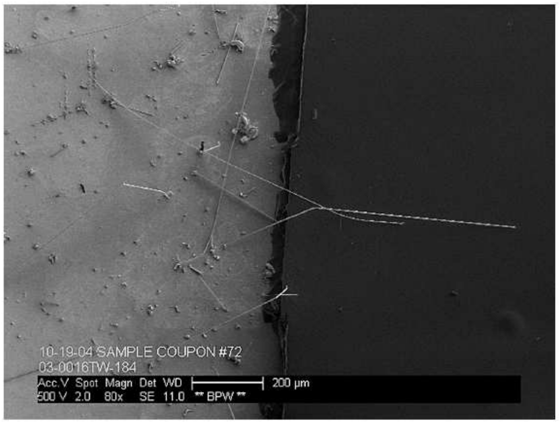
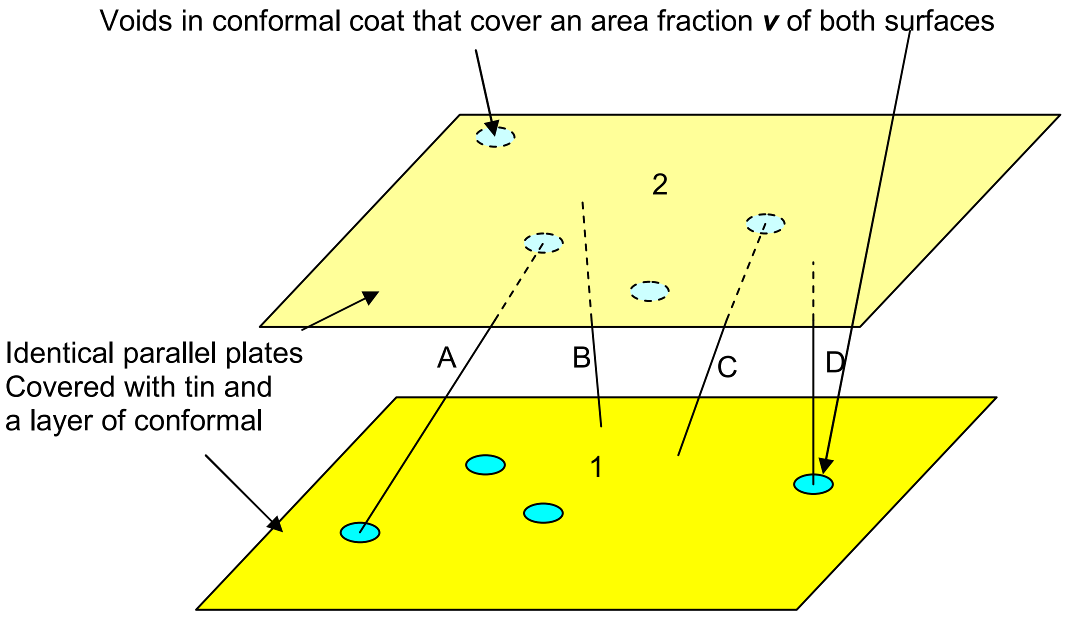


Figure 9. The density of whiskers that have formed on the uncoated half of this image significantly exceeds the density that have emerged from the coated half.

The model described below has been constructed based upon three assumptions:

- Conformal coat on real circuits exhibits a certain amount of voids
- Conformally coated tin-plated surfaces will grow whiskers at a reduced incidence
- Whiskers cannot penetrate a conformally coated surface at a distance from the origin of the whisker.



Whisker A-grows from void area on plate 1, and contacts void on plate 2- short
Whisker B-grows through coating on plate 1, and contacts coating on plate 2- no short
Whisker C-grows through coating on plate 1, and contacts void on plate 2- short
Whisker D-grows from void area on plate 1, and contacts coating on plate 2- no short

Figure 9. Simplified model to describe whiskers that bridge between parallel plates that are imperfectly coated.

Conformal Coat Model

Consider two identical parallel plates, each covered with a layer of tin and a layer of conformal coat that exhibits incomplete coverage. Let *v* represent the fraction of each surface that is void of conformal coat.

Let *P(u)* represent the probability that a whisker will form per unit area of the surface which is un-coated, and grow sufficiently that it eventually comes into contact with the opposing surface.

Let *P(c)* represent the probability that a whisker will form beneath a unit area of the surface which is coated, penetrate the coating, and grow sufficiently that it eventually comes into contact with the opposing surface.

The probability that a whisker will grow from one of the plates, bridge the intervening space, and contact the opposing plate is given by:

$$P(1 \rightarrow 2) = (1-v)P(c) + vP(u)$$

Equation 4

The probability is identical for whiskers bridging in the opposite direction, by symmetry.

Assume that whiskers which bridge the gap between the plates and eventually contact a portion of the opposing plate that is covered by conformal coating will not result in electrical contact [5]. The model is illustrated in Figure 9 above.

There are two distinct modes by which electrical shorting could occur: (1) a whisker bridges the gap and contacts a region of the opposing surface that is not coated; or (2) whiskers grow simultaneously from opposite sides and contact each other in the space between the plates.

Let P_1 represent the probability of a whisker contacting a portion of the opposing surface which is void of conformal coat. This is given by:

$$P_1 = v\left[(1-v)P(c) + vP(u)\right]$$

Equation 5

Let P_2 represent the probability that two whiskers grow from opposite surfaces, to meet in the middle. Precise estimation of this probability will be very difficult. It will depend upon the probability that a pair of whiskers will grow from opposite sides, exhibiting complementary lengths and orientations. Monte Carlo techniques could be employed to make an estimation, but this will be complicated by the fact that whiskers move over time. For estimation purposes we'll approximate the probability that such a pair of whiskers will grow is proportional to the probability that a pair of bridging whiskers will grow. The probability is estimated by:

$$P_2 \approx F\left[(1-v)P(c) + vP(u)\right]^2 \qquad \text{Equation 6}$$

Where *F* is a term of unknown form that accounts for the particulars of the geometry and any mutual affinity that the whiskers may exhibit. It is assumed that this term does not depend upon neither *P(c)* nor *P(u)*.

Let P_T represent the total probability that a short will form due to whisker growth on either surface, either contacting a void for another whisker. This is given by the sum:

$$P_T = 2(P_1 + P_2) \qquad \text{Equation 7}$$

By combining equations 5, 6, and 7:

$$P_T = 2\left\{v\left[(1-v)P(c) + vP(u)\right] + F\left[(1-v)P(c) + vP(u)\right]^2\right\}$$

Equation 8

Let *E* represent a quantity called the "Coating Effectiveness". This quantity is factor by which the conformal coat suppresses the formation of whiskers exhibiting bridging geometries. That is:

$$E = {P(c)}/{P(u)} \qquad \text{Equation 9}$$

Replacing *P(c)* with the value *EP(u)* Equation 8 becomes:

$$P_T = 2\left\{\left[v(1-v)\right]EP(u) + v^2P(u)\right\} + F\left\{(1-v)EP(u) + vP(u)\right\}^2$$

Equation 10

By algebra from Equation 10:

$$P_T = 2P(u)\left(Ev - Ev^2 + v^2\right) + 2FP^2(u)\left(E - Ev + v\right)^2$$

Equation 11

In the case of a void-free coating, the value of *v* goes to zero, and the equation reduces to:

$$P_T = 2FE^2P^2(u) \qquad \text{Equation 12}$$

In the case of a coating that provides perfect whisker suppression, but exhibits voids, the value of E goes to zero and Equation 11 reduces to:

$$P_T = 2v^2\left[P(u) + FP^2(u)\right] \qquad \text{Equation 13}$$

In a case where the coating provides substantial yet imperfect whisker suppression, and exhibits a non-zero, but small void fraction, the following approximation holds:

$v \prec\prec 1$ and $E \prec\prec 1$

In this case the higher-order terms become insignificant and Equation 8 can be approximated by:

$$P_T \approx 2P(u)\left(Ev + v^2\right) + 2FP^2(u)\left(E^2 + v^2\right)$$
Equation 14

If it is also the case that the probability that a whisker will form from an uncoated surface that is sufficient to bridge the gap is also very small, the implication is that:

$P(u) \prec\prec 1$

If this assumption is also true, then Equation 11 can be reduced even further to:

$$P_T \approx 2P(u)\left(Ev + v^2\right) \qquad \text{Equation 15}$$

The factor in the Equation 15, $Ev+v^2$, provides an approximation of the overall reduction in the probability of creating a short that can be gained by an application of conformal coat that exhibits a void fraction of v, and a "Coating Effectiveness" of E (providing that the small-value assumptions listed above are valid). This new factor depends both upon the physical properties of the conformal coat, which determine E, and how the coating is applied which determines the void fraction v. The portion of the term that accounts for whiskers growing through the conformal coat is given by Ev , while v^2 accounts for whiskers that grow from an uncoated surface.

Predictions

Consider the case of conformal coat which can suppress whisker growth by a factor of 10:1, and is applied with a surface area void fraction of 5%. Inserting these values into Equation 15 above, and overall reduction in the probability of whisker shorts is predicted to be only 0.0075 of the probability without the conformal coat. From this example, it can be seen at conformal coats that exhibit fairly mediocre properties can still provide significant amounts of risk mitigation.

A higher-quality coating that provides 100:1 effectiveness, while exhibiting only a 0.5% void fraction is predicted to reduce the incidence of whisker shorts to only 0.0000525 of the original value. These are not unreasonable goals for a practical coating.

Discussion of model assumptions

One critical assumption is that the overall whisker density is such that the probability of whiskers pairs touching in the middle can be ignored. Whisker density measurements have been reported over a very wide range. Specimens that have been prepared especially to produce large quantities of long whiskers have been reported to grow whiskers at densities exceeding 2000 per square millimeter [3]. Measurements performed on platings more typically encountered in production have yielded results in the range of between 50 and 150 per square millimeter [3,4].

A typical SOIC lead exhibits a surface area along its edge of approximately one half of the square millimeter. Using the results discussed above for the whisker-prone plating analyzed by Hilty and Corman, there could be many tens of whiskers growing from the side of one such lead with a length that exceeds 50% of the gap size. Clearly, whisker to whisker shorting should not be ignored, for such plating. If one considers the "whisker mitigated" plating described by Hilty and Corman, or the plating analyzed by Fang, Osterman, and Pecht, the expected value for a whisker with a length greater than 50% of the gap size to grow on the side of such lead will be much less than one. For platings of this sort, the risk of whisker to whisker shorts will be negligible.

Nowhere in these calculations does the spacing between the plates appear. The implication is that for this approach to be valid that the Coating Effectiveness, ***E***, must not be a function of the gap dimension. Another way to say this is that the coating is equally effective in suppressing the formation of short and long whiskers. Verification of the validity of this assumption must be tested by performing statistical analysis on the length of whiskers that penetrated coating in comparison to an identical non-coated surface. An investigation of this sort is planned.

It is assumed that the probabilities for whisker formation, coating voids, and coating destinations are all uniformly distributed and independent of one another. This is a reasonable assumption for infinite, uniform, parallel plates. For non-idealized geometries the model will not be too bad so long as the probabilities remain independent. If, however, the probabilities are strongly dependent on one another the model will break down. That is to say if the same location is at an elevated risk for both a coating void and whisker growth, or for both being a A typical SOIC lead exhibits a surface area along its edge of approximately one half of the square millimeter. Using the results discussed above for the whisker-prone plating analyzed by Hilty and Corman, there could be many tens of whiskers growing from the side of one such lead with a length that exceeds 50% of the gap size. Clearly, whisker to whisker shorting should not be ignored, for such a plating. If one considers the "whisker mitigated" plating described by Hilty and Corman, or the plating analyzed by Fang, Osterman, and Pecht, the expected probability of a whisker with a length greater than 50% of the gap size to grow on the side of such lead will be much less than one. For platings of this sort, the risk of whisker to whisker shorts will be negligible.

With regards to conformal coating, it should be noted that nowhere in the derived calculations does the spacing between the plates appear. The implication is that for this approach to be valid that the Coating Effectiveness, ***E***, must not be a function of the gap dimension. Another way to say this is that the coating is equally effective in suppressing the formation of short and long whiskers. Verification of the validity of this assumption must be tested by performing statistical analysis on the length of whiskers that penetrated coating in comparison to an identical non-coated surface. An investigation of the sort is planned.

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The circuit application of most common concern is that of adjacent tin-plated leads on a single electronic package. In this case the parallel surfaces will not be large in extent. The difference between finite leads and large parallel surfaces is that some whiskers that would have contacted in large neighbor will miss a small one. Since the model only compares the difference between coated and uncoated performance, this approximation should have little or no effect on the general form of the results. In other words, for both the coated and uncoated cases we are considering only those whiskers which actually contact the neighbor.

The application of this model to actual circuit configurations requires that data be collected both on the actual void fraction of the conformal coat, and the ability of the conformal coat to suppress whisker growth given its actual thickness range. The void fraction will depend upon coating material and process, and also upon the details of the electronic package whose leads are being coated. Assessments of this type are currently being planned. It is recommended that investigators collect data of this type so that better predictions can be made.

The concern about whiskers that "tunnel" beneath a conformal coat needs to be considered in light of the actual geometry being evaluated. For the case of adjacent leads of a single microelectronics package the region of concern for this phenomenon is limited to the portion of the lead that is immediately adjacent to the package. This region will represent a small fraction of the total surface area of the leads, which would tend to reduce the probability that this will be a problem.

If the geometry of interest is adjacent tin-plated runs on the surface of the circuit card, the opportunity for whisker "tunneling" will be significantly larger than in the case of adjacent leads.

Incorporation into risk assessment algorithms

Using the results of the model to enhance the risk assessment algorithm will require the collection detailed data regarding the properties of actual conformal coat as applied to a variety of component types. Once this has been performed, mitigation factors can be estimated which can then be used to provide input to the algorithm. The logic used in the algorithm will need to be adjusted so that this factor is discounted for situations where extremely high whisker densities are anticipated, to account for the possibility of whisker to whisker shorts.

Conclusions and Recommendations

Whisker length distribution data indicates that shorter whiskers are more common than longer whiskers, (over the range of distances practical concern). Since the whiskers that are available to create bridges are only those longer than the gap size, the risk of whisker shorts will decrease dramatically as the gap increases. Conservative risk assessment procedures and tools may be based upon the Survival Function of the applicable whisker length probability distribution.

Conformal coating will provide significant levels of mitigation, provided that the probability of whisker to whisker shorts is negligible. The probability of whisker to whisker shorts may be significant in cases where the overall whisker density is extremely high. The degree of mitigation that can be provided by actual conformal coating systems can be estimated if the incidence of coating voids and the ability of the coating to suppress whisker growth are both quantified. Investigations to quantify these properties are planned and recommended for those who must justify the use of conformal coating as a mitigation strategy should be pursued.

Acknowledgments

Thanks to Bob Hilty of Tyco Corp. and Mike Osterman of the University of Maryland CALCE Center for sharing their whisker length data. Thanks also to Tom Woodrow of Boeing for permitting me to use his conformal coat image. Thanks also to Mark Kostyla of Raytheon Co. for performing scanning electron microscopy in support of this investigation.

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