Failure Probability Evaluation Due to Tin Whiskers Caused Leads Bridging on Compressive Contact Connectors

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***Abstract*—This paper presents a failure probability assessment of compressive contact connectors due to tin whiskers caused leads bridging. Based on scanning electron microscope measurements, we establish probability distributions of four involved variables: whisker length, orientation, origin location, and counts. A failure probability model is developed and used to calculate the failure probability in terms of two types of failure definition: 1) National Electronics Manufacturing Initiative (NEMI) acceptance criteria, and 2) leads bridging caused by tin whiskers. Results indicate that, in terms of the NEMI criteria, there is more than a 50% chance that the connectors would fail to meet the maximum allowable whisker length for Class 2 products at six-month ambient storage, while the probability goes up to 74% for Class 2, or 62% for Class 3 at one year. However, the failure probability for tin whisker caused leads bridging is fairly low, only 0.0002% for six-month storage, 0.0074% for one-year storage, and even 0.0515% for five-year storage. Therefore, although the connectors may fail to meet NEMI acceptance criteria for maximum allowable whisker length, the whiskers do not pose significant field risk to cause leads bridging at ambient storage.**

***Index Terms*—Failure probability, multiple random variables, Poisson distribution, three-parameter Weibull distribution, tin whisker.**

ACRONYM[1]

SEM	Scanning electron microscope
NEMI	National Electronics Manufacturing Initiative
PCB	Printed circuit board

NOTATION

$L(t)$	length of a tin whisker as a function of time t
θ	orientation of a tin whisker
Y	origin coordinate of a tin whisker
N	whisker counts on a longitudinal edge of contact area
S	spacing between two adjacent leads on a compressive contact connector
$L_{\max}$	maximum achievable whisker length
λ_G	growth rate of tin whisker
β	shape parameter of Weibull distribution
η	scale parameter of Weibull distribution
γ	location parameter of Weibull distribution
$g_\theta(\theta)$	*pdf* of orientation θ
$h_Y(y)$	*pdf* of origin coordinate Y
$P_N(N=n)$	probability mass function of whisker counts N
λ_{seg}	Poisson parameter of whisker counts on a SEM inspection segment
λ	Poisson parameter of whisker counts on a longitudinal edge of contact area
H	half height of a longitudinal edge of contact area
$P_1(t)$	probability due to a single whisker caused leads bridging
$P(t)$	probability due to all possible whiskers caused leads bridging
AL	NEMI recommended acceptance level for tin whisker length

I. INTRODUCTION

DRIVEN by government legislation [1], [2] and market forces, Pb-free electronics have been implemented in most consumer products. As a result of this implementation, pure tin or high tin Pb-free alloy finishes are widely adopted to replace Pb finishes, due to low cost, corrosion resistance, and compatibility with both Pb, and Pb-free solders [3], [4]. However, one annoying byproduct accompanied with this transition is the formation and growth of tin whiskers. Tin whiskers have generated a lot of reliability concerns because the needle-like conductive crystal whisker can grow up to hundreds, even thousands of microns, and cause electric short by bridging pins or leads [5], [6]. Field electric failures due to tin whiskers have resulted in huge losses, even in millions of dollars [7], [8]. So, to assess potential risk posed by tin whiskers, the National Electronics Manufacturing Initiative (NEMI) of the United States and European Semiconductor Collaboration E4 have proposed whisker length acceptance criteria for different classes of products [9], [10]. But a critic might argue that the criteria do not consider the geometry of a part, which plays a big role on the risk. For example, larger spacing between leads tends to have a lower risk for leads bridging. So far, due to lack of thorough understanding of whisker formation and growth

Manuscript received June 24, 2007; revised January 28, 2008; accepted February 29, 2008. First published July 9, 2008; current version published September 4, 2008. Associate Editor: J. C. Lu.

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Digital Object Identifier 10.1109/TR.2008.927704

[1]The singular and plural of an acronym are always spelled the same.

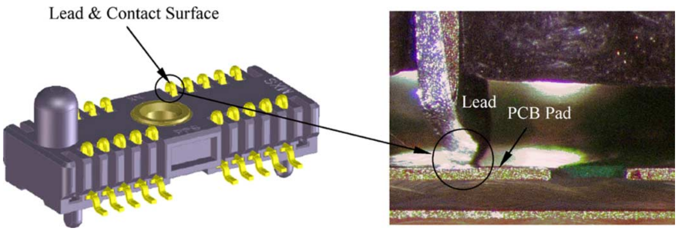


Fig. 1. Sketch of a compressive contact connector.

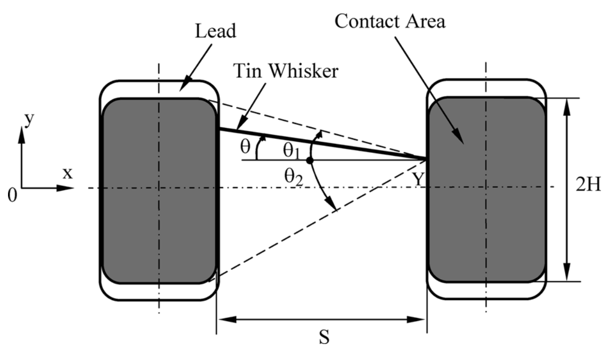


Fig. 2. Schematic showing a tin whisker bridging two adjacent leads.

mechanisms, no universal model has been established to quantify the risk. Most publications on the field risk assessments are limited to presentations of field failure data [11]–[15]. Quantitative analysis based on failure probability modeling is scarce. Furthermore, what makes the risk assessment even more complicated is the field risk posed by tin whiskers varies from part to part, such that any risk assessment established for one part may be only applicable for that specific part.

This paper presents a failure probability assessment of compressive contact connectors due to tin whiskers caused leads bridging. This type of connector is widely used in consumer electronics to provide electrical interfaces. When being assembled into products, the leads of the connectors, made from phosphor bronze with a plating finish of matte tin over a layer of nickel, are compressed to make contact with PCB pads. Large contact force causes the leads to be in permanent plastic deformation in the contact areas, resulting in surface tension change, and aggravating tin whisker growth. Whiskers generated from the edge of the contact area grow faster and longer than from non-contacted areas, posing a bigger risk for bridging leads.

II. Failure Definition of Tin Whiskers Caused Leads Bridging

A typical compressive contact connector is shown in Fig. 1. Assume the contact area is rectangular with the same width as the lead and tin whiskers grow in the contact area plane. Then, leads bridging occurs when a tin whisker, which originates at one lead, reaches out to the adjacent one, as shown in Fig. 2. It should be noted that, in reality, the whiskers could grow in any direction. But from inspection of disassembled connector samples, many whiskers grow approximately in the contact area plane. Moreover, the in-plane whiskers need the shortest length to bridge adjacent leads, implying highest bridging probability.

TABLE I
Mean Values of Whisker Length at Two Time Points of Ambient Storage

Storage Time (in months)	3	5
Mean Value of Whisker Length (in μm)	40	60

Hence, only the whiskers growing in the contact area plane are considered.

Among the in-plane whiskers, only those growing outward from the longitudinal edges (in y direction) of the contact area can cause leads bridging. Noting that the edges have finite extent, a whisker originating at a Y coordinate causes bridging if

$$L(t) \times \cos\theta \geq S, \quad -\theta_2(Y) \leq \theta \leq \theta_1(Y), \tag{1}$$

where $\theta_1(Y)$, and $\theta_2(Y)$ are the outmost angles with which the whisker could cause leads bridging, as functions of Y.

III. Probability Distributions of Whisker Length, Orientation, Origin, and Counts

At any specific time t, the whisker length varies from one piece to another. Also, the whisker can grow in any orientation with origin at any y-axis coordinate. Hence, $L(t)$, θ, and Y are all random variables; and the failure probability assessment depends on the probability distribution functions of these variables. Furthermore, any whisker growing outward from the longitudinal edge has a potential to cause bridging failure. Hence, the bridging failure probability also depends on the number of whiskers along the longitudinal edge. Denote the whisker counts as N. Then, N adds another random variable, and the failure probability involves four random variables.

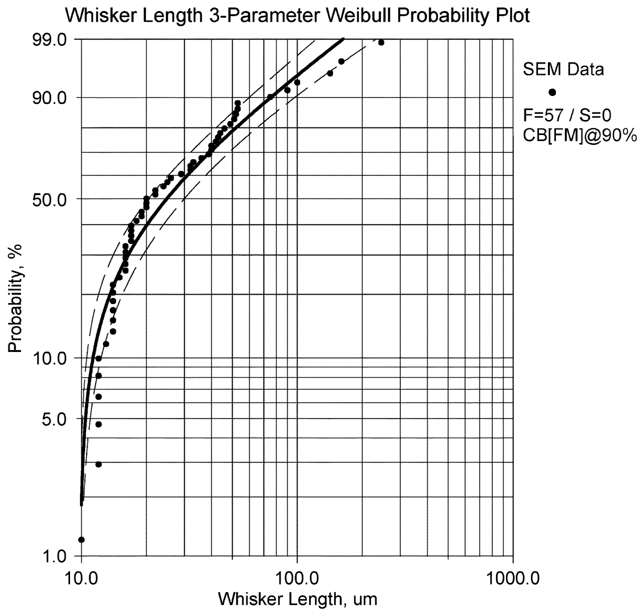
A. Whisker Growth Model, and Whisker Length Distribution

Although several growth models have been reported [14]–[17], a simple but widely used one is expressed by a convex exponential function as

$$L(t) = L_{\max} \cdot (1 - e^{-t/\lambda_G}). \tag{2}$$

This model reflects the fact that whisker growth gets saturated eventually due to the driving force from inter-metallic chemical reaction being saturated.

The growth rate λ_G depends on many factors. In general, all design and manufacturing parameters would affect the growth rate, such as lead materials, finish material compositions, finish coating thickness, electronic packaging procedures, reflow profile, etc. Hence, the growth rate data presented in publications may not be applicable to a different part even with smallest variation. For the compressive contact connectors discussed here, Table I lists mean values of tin whisker length measurements. These data are taken from two batches of samples at different time points of ambient (room temperature) storage: one at three months, and the other at five months. Based on the data, the growth rate is calculated as $\lambda_G = 9.0$ months. For comparison, the growth rate on bright tin finish over brass is reported



β=0.82, η=23.54, γ=9.82

Fig. 3. Whisker length probability plot.

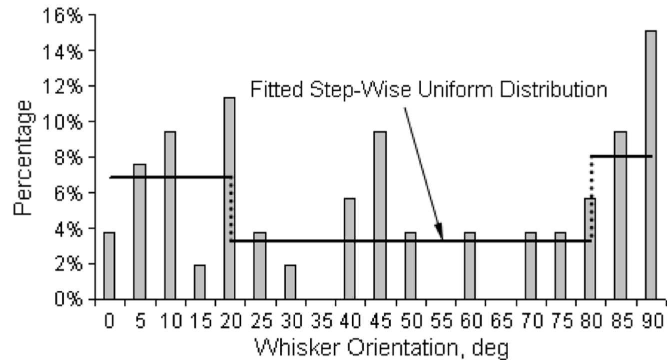


Fig. 4. Whisker orientation distribution plot.

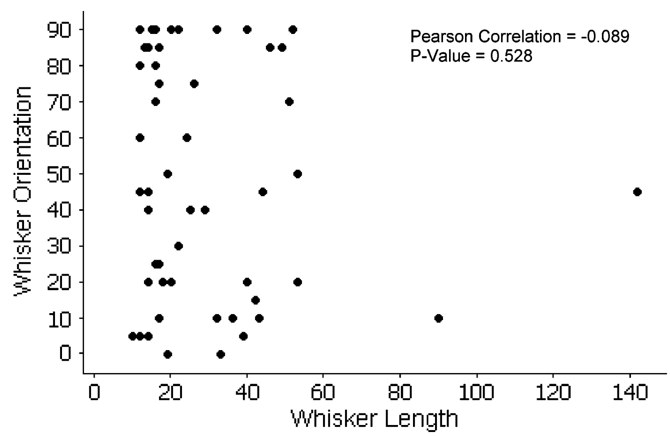


Fig. 5. Scatterplot to show correlation between whisker length and orientation.

as 5.0 months [14]. Clearly, the compressive contact connectors have a larger number of λ_G, implying a longer time to get whisker growth to be saturated.

Considering whisker length as a random variable function of time t, (2) represents the characteristic length. Fig. 3 shows a three-parameter Weibull probability plot of whisker length measurements from 15 connector samples. The samples are taken from real products disassembled after ambient storage for three months. These measurements are taken by using a scanning electron microscope (SEM). From each sample, multiple leads are randomly selected. And on each lead, a 116.0 μm long segment is randomly chosen for the SEM inspection. The segment is on a longitudinal edge of the contact area. Only whiskers longer than 10 μm are recorded because shorter ones are considered to carry low risk of causing leads bridging. From Fig. 3, the fitted location parameter γ is approximately equal to 10 μm, matching the data record cut-off threshold of 10 μm.

For a three-parameter Weibull distribution, both the scale and location parameters follow the whisker growth model (2). Based on the distribution parameters obtained from the data at three-month ambient storage, the whisker length $L(t)$ follows a three-parameter Weibull distribution with the parameters as

$$\begin{aligned} \beta &= 0.82, \\ \eta(t) &= 83.04 \times (1 - e^{-t/\lambda_G})\ \mu\text{m}, \\ \text{and } \gamma(t) &= 34.64 \times (1 - e^{-t/\lambda_G})\ \mu\text{m}. \end{aligned}$$

B. Whisker Orientation Distribution

From the same SEM inspection as described in Section III-A, whisker orientation data are also collected. Fig. 4 shows the orientation histogram. The data are best fitted by a step-wise uniform distribution, which has been used for bright tin platting over brass [14]. Fig. 5 provides evidence that there is no clear indication of correlation between the whisker length, and orientation. Hence, it is proper to assume the whisker length and orientation are independent of each other.

Noting that a whisker can grow in any angle, the orientation distribution established above should also apply to negative angles. Hence, the *pdf* of the orientation θ is expressed as

$$g_\theta(\theta) = \begin{cases} 0.0120, & -90^\circ \le \theta < -80^\circ, \\ 0.0035, & -80^\circ \le \theta < -20^\circ, \\ 0.0085, & -20^\circ \le \theta < 20^\circ, \\ 0.0035, & 20^\circ \le \theta < 80^\circ, \\ 0.0120, & 80^\circ \le \theta < 90^\circ. \end{cases}$$

C. Whisker Origin Location Distribution

Also collected from the SEM inspection is whisker origin location data, which indicate that the origin location can be assumed to follow a uniform distribution. Hence, the *pdf* of the origin coordinate Y is expressed as

$$h_Y(y) = \frac{1}{2H}, -H \le y \le H.$$

D. Whisker Counts Distribution

Whisker counts do not increase over time [15]. Hence, the whisker counts data obtained from the SEM inspection after three-months of ambient storage can be used to establish the counts distribution. Fig. 6 shows a histogram of the whisker counts on the 116.0 μm long segment. From Fig. 6, it is proper to assume the whisker counts follow a Poisson distribution, and its parameter is calculated as $\lambda_{seg} = 5.06$.

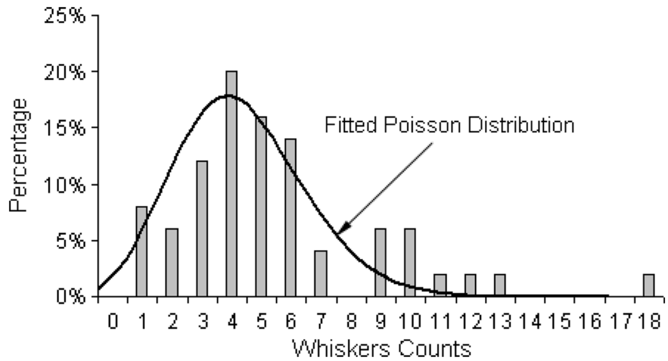


Fig. 6. Whisker counts distribution plot.

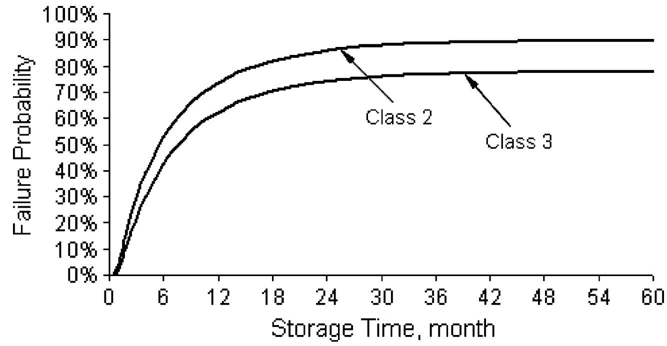


Fig. 7. Failure probability plots in terms of NEMI acceptance criteria.

Noting that the summation of independent Poisson variables follows a Poisson distribution with a parameter of summation of individual Poisson parameters, and the overall height of a longitudinal edge is $2H$, the whisker counts on a whole longitudinal edge approximately follow a Poisson distribution with a parameter of

$$\lambda = \lambda_{seg} \cdot \frac{2H}{116} = \lambda_{seg} \cdot \frac{H}{58}. \tag{3}$$

Denote $P_N(N = n)$ to be the Poisson probability mass function of the whisker counts N on a longitudinal edge. Then,

$$P_N(N = n) = \frac{e^{-\lambda} \cdot \lambda^n}{n!}, \qquad n = 1, 2, \ldots \tag{4}$$

IV. Failure Probability Model Development

With the distribution functions of $L(t)$, θ, Y, and N having been established, a model can be developed to assess the probability of tin whiskers caused leads bridging failure.

A. Failure Probability Due to a Single Whisker Caused Leads Bridging

Denote the pdf of whisker length $L(t)$ as $f_L(x;t)$ at time t. Then, according to Fig. 2, the failure probability due to a single tin whisker caused leads bridging is expressed, given its origin at y coordinate, as

$$\begin{aligned} P_1(t|Y=y) &= \Pr\{\{L(t)\cdot\cos\theta \geq S\} \cap \{\theta_2(y) \leq \theta \leq \theta_1(y)\}\} \\ &= \int_{\theta_2(y)}^{\theta_1(y)} \mathrm{d}\theta \int_{\frac{S}{\cos\theta}}^{+\infty} f_L(x;t)\cdot g_\theta(\theta)\cdot dx, \end{aligned} \tag{5}$$

where $\theta_1(y) = \arctan((H - y)/S)$, and $\theta_2(y) = -\arctan((H + y)/S)$.

Then, considering the whisker origin location as a random variable, the failure probability becomes

$$\begin{aligned} P_1(t) &= \int_{-H}^{H} P_1(t|Y = y)\cdot h_Y(y)\cdot dy \\ &= \int_{-H}^{H} h_Y(y)\cdot dy \int_{\theta_2(y)}^{\theta_1(y)} \mathrm{g}_\theta(\theta)\cdot \mathrm{d}\theta \int_{\frac{S}{\cos\theta}}^{+\infty} f_L(x;t)\cdot dx. \end{aligned} \tag{6}$$

Because multiple integrals are involved in (6), a numerical algorithm may be needed to calculate $P_1(t)$.

B. Failure Probability Due to Multiple Whiskers Caused Leads Bridging

If multiple whiskers exist, each piece can cause leads bridging. Assuming these whiskers are independent of each other. Then, for a given number of whiskers, N, the failure probability is

$$P(t|N) = 1 - [1 - P_1(t)]^N. \tag{7}$$

Considering the number of whiskers as a random variable, the failure probability due to multiple whiskers caused leads bridging becomes

$$P(t) = \sum_{n=0}^{+\infty} P(t|N)\cdot P_N(N = n). \tag{8}$$

Combined with the distribution functions established in Section III, (6)–(8) consist of a complete set of equations to assess the failure probability of the compressive contact connectors due to tin whiskers caused leads bridging.

V. Failure Probability Assessment

Failure probability assessment of the compressive contact connectors due to tin whiskers caused leads bridging is performed in this section.

A. Failure Probability in Terms of NEMI Acceptance Criteria

NEMI has proposed acceptance levels of maximum allowable whisker lengths for three different classes of products [9], [10]. Except for Class 1 products, which forbid use of pure tin or high tin content alloys, the acceptance level is 40 μm for Class 2 products, which are used for high reliable business applications; and 50 μm for Class 3 products, which are used for most consumer products with relatively short product lifetime, typically five years as maximum.

Using the whisker length distribution established in Section III-A, the probability that a compressive contact connector fails to meet the NEMI criteria is given by

$$\Pr\{L(t) \geq AL\} = e^{-\left[\frac{AL-\gamma(t)}{\eta(t)}\right]^\beta}. \tag{9}$$

Fig. 7 shows the failure probability plots for Class 2 and 3 products. For Class 2 products, even at six-month ambient storage,

TABLE II
LEAD AND CONTACT AREA DIMENSIONS

Nominal Spacing S (in μm)	Nominal Width W (in μm)	Mean Value of Half Height H (in μm)
850	350	150

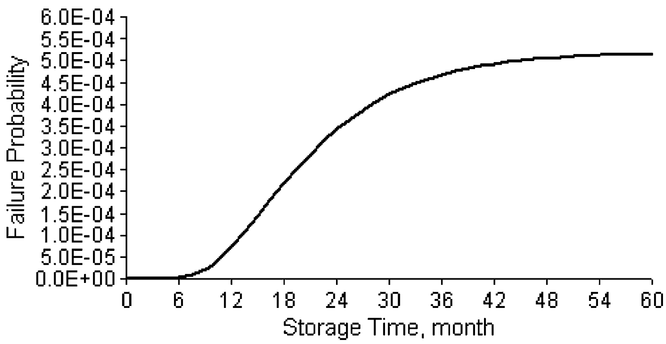


Fig. 8. Failure probability plot in terms of tin whiskers caused leads bridging.

there is more than a 50% chance that a compressive contact connector would fail to meet NEMI criteria. If the storage time increases to one year, the failure probability goes up to 74%. Similarly, for Class 3 products, the failure probability is 62% at one-year ambient storage. The maximum failure probability is 90% for Class 2 products, and 78% for Class 3 products.

B. Failure Probability in Terms of Leads Bridging

Failure probability due to tin whiskers caused leads bridging depends on the geometry of spacing between leads. Table II list some dimensions of the compressive contact connectors, plus a mean value of the half height, H, measurements taken from the SEM inspection. Plugging these numbers into (6)–(8), the failure probability is calculated.

Fig. 8 shows the probability plot. It can be seen that the failure probability increases at the beginning, and then decelerates after about two years of storage because tin whisker growth is getting saturated. Overall, the probability value is fairly low, with a number of only 0.0002% at six-months storage, 0.0074% at one-year storage, and even 0.0515% at five-years storage. Hence, the field risk posed by potential tin whiskers caused leads bridging is fairly low at ambient storage.

Based on the results obtained above, although it is likely for a compressive contact connector not to meet NEMI acceptance criteria for maximum allowable whisker length at ambient storage, the field risk posed by tin whiskers for leads bridging is fairly low. However, this statement may not be valid for other types of connectors. Even a slight change of design and manufacturing processes could make the statement false.

ACKNOWLEDGMENT

This work was mostly accomplished during the author's employment with Seagate Technology, PSG Design Center. Karen Camic performed SEM inspection. Mike Ries, and Paul Beatty provided valuable suggestions for failure probability model development.

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