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Statistical analysis of tin whisker growth

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Abstract

As the result of the global movement to lead-free electronics, companies which assemble semiconductor devices are switching from finishes incorporating lead to pure tin or high tin lead-free alloys. This transition has resulted in a reliability issue, concerning the formation of conductive tin whiskers which can grow across leads of a package and cause current leakage or short circuits. This paper presents the results of an experimental tin whisker growth study of bright tin on brass substrates. A probabilistic model is applied to describe the phenomenon of whisker growth in terms of whisker density, length and growth rate.

1. Introduction

A transition to lead-free electronics has been driven by market forces [1] and government legislations, including European WEEE and RoHS directives [2]. Electronic parts manufacturers who fail to transition to lead-free products may find themselves excluded from the European and the other global markets. As a result, electronic component manufactures have widely adopted pure tin and high tin lead-free alloy finishes, due to low cost and compatibility with both lead and lead-free solders.

A major drawback of using pure tin and high tin alloy finishes is tin whisker formation. A tin whisker is a crystal, which grows from the tin finished surfaces, generally as a needle-like protrusion. Tin nodules may also can produce from the surface; but they are by short and do not pose serious risk to electronic products.

The potential risks posed by tin whiskers include current leakage short circuits, metal vapor arcing and plasma at low pressure condition, and a source of debris and contamination. Reports from the electronics industry indicate numerous electronic field failures associated with tin whiskers have been observed in electronic assemblies, particularly in the late 1980s and early 1990s, which resulted in millions' of dollars loss [3]. To reduce the potential risks posed by tin whiskers, various mitigation studies [4], test criteria developments [5], and risk and reliability assessments [6–8] have been launched by the electronics industry and customers. Nevertheless, despite over 60 years of study, whisker growth mechanisms are still not well understood and there are no standard accelerated tests or prediction method for whisker growth.

2. Electronics industry's acceptance levels for whisker growth

In order to limit the risks posed by tin whiskers to electronic products, some electronic companies

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Table 1
NEMI's whisker length limits [8]

Maximum whisker length			
Device (package type, lead pitch or operating frequency)	Class 1	Class 2	Class 3
Discrete device (2 pins) Multi-lead packages	Pure tin and high tin content alloys not acceptable	40 μm	67 μm (Minimum gap between leads ~ 0.05 mm)/3 or 67 μm, whichever is smaller
Operating frequency > 6 GHz (RF) or t_{rise} < 59 ps (digital)			50 μm

proposed acceptance levels. For instance, the European semiconductor collaboration E4, formed by Philips, Infineon, STMicroelectronics and Freescale Semiconductor, was the first manufacturers to develop whisker acceptance levels with recommended test conditions [9]. A length of 50 μm was chosen as the maximum whisker length at the device end-of-life. The National Electronics Manufacturing Initiative (NEMI) [8] proposed to create a standardized whisker growth limit and proposed maximum allowable whisker lengths for three classes of products, as shown in Table 1. Class 1 is assigned to mission and life critical high-reliability applications, such as military, space and medical applications. Class 2 is for high-reliability business applications, such as telecom infrastructure equipment and high-end servers. Class 3 is suitable for consumer products with relatively short product lifetimes (typically five years maximum).

The E4 and NEMI acceptance levels may not represent the real risks posed by whiskers since only whisker length is considered in the levels. Other factors, such as whisker density, growth rate and the geometry of the electronic parts on which whiskers develop are also the key factors to reflect the real risk by whiskers.

3. Experimental study

Our experimental study was conducted on heat-treated bright tin over brass (type 260) coupons. The thickness of the bright tin plating was 5 μm. The heat-treatment was annealing (1 week after plating, 150 °C for 2 h) followed by temperature/humidity (T/H) at 60 °C/95%RH for 2 weeks. After the exposures, the coupons were stored in room ambient environment and whiskers were measured after 8, 13 and 18 months.

In our study, tin whisker growth was expressed in terms of whisker density, length and growth rate since these three parameters determine risk posed by tin whiskers for a specific application. Whisker density is the count over a fixed area, such as the number of whiskers per square centimeter. Whisker length refers to the length of a whisker beyond the plating surface from which a whisker grows. Growth rate describes time-dependent length of a whisker.

The counting procedure for the density calculation was (1) to observe whiskers with scanning electron microscope (SEM); (2) to count whiskers greater than 10 μm in length; and (3) to calculate density and measure length from 30 randomly selected sites for each coupon. An optical microscope cannot be used to observe whiskers because it does not have high enough magnification and cannot distinguish whiskers from dusts. A SEM has high magnification and can take very clear pictures of the observed sites. The threshold was set to 10 μm because whiskers, whose length is smaller than 10 μm, should not cause serious reliability risks and can be excluded. Considering the length limits proposed by E4 and NEMI as described previously, our limits are more conservative.

The average whisker density is the ratio of the number of whiskers per observed site area, for the 30 sites analyzed. It is assumed that the measured local whisker density always approaches the real whisker density.

4. Test results

Measurements on whisker density and length were conducted for the coupon of bright tin over brass in the 8th, 13th and 18th month storage in room ambient. The results of the measurements are presented in Table 2. The whisker density during the periods of the three measurements increased with time. However, it appears

Table 2
Results of the three measurements on whisker density

Measurement time	8-month storage	13-month storage	18-month storage
Average density (#/cm^2)	14240	14360	14520
Standard deviation	5490	4820	3180
Density increasing rate (%)	–	1.1	0.8

that the density was approaching an equilibrium state, which suggests that no new whiskers will appear.

The test results suggest that there is an incubation period for whiskers to form. This is consistent with NASA's findings as well [10]. The incubation period is a concern because it affects the test time. The test time should be beyond the incubation period in order to obtain the whole whiskering propensity for a particular application.

Maximum length is often used to describe whiskering propensity and risk [11]. In this study, whisker length is quantified by a fitted distribution to show over time. Fig. 1 shows the whiskers length bar distribution for the coupon of bright tin plated over brass in the 8th month storage in room ambient. It can be seen that whisker length in the range of 20–30 occupied the largest percentage, followed by the range of 10–20 μm and the range of 30–40 μm, respectively. The collected data were fitted into a lognormal distribution. The mean was 24.0 μm and the standard deviation was 12.7 μm. The goodness of the fitting was 0.9997.

Fig. 2 illustrates the whisker length bar distribution in the 13th month storage in room ambient, again for the coupon of bright tin plated over brass. Whiskers, whose length ranged from 10 to 40 μm, still dominated the percentage. Compared to the first measurement, the percentage of whiskers ranging from 10 to 20 μm decreased, while whiskers with the range of 30–40 μm increased in percentage and became the second largest group for this time period. This phenomenon indicates that whiskers, as a whole group, continued to grow in length during the four-month storage in room ambient. A lognormal distribution was still used to fit the data. The mean and standard deviation were 25.7 and 11.5 μm respectively. The fitting goodness was 0.9976.

The whisker length bar distribution in the 18th month storage in room ambient for the coupon of bright tin plated over brass is shown in Fig. 3. There was an apparent decrease in percentage for whiskers in the range of 30–40 μm and an apparent percentage increase of whiskers length ranging from 40 to 50 μm. The change of the distribution suggests that whiskers grew in length in the five month period. The mean and standard deviation of the fitted lognormal distribution changed to be 26.0 and 11.4 μm respectively. The fitting goodness of this measurement was 0.9967.

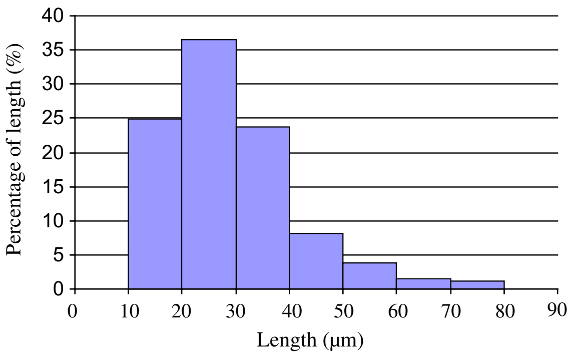

Fig. 1. Bar-distribution of whisker length in the 8th month storage in room ambient.

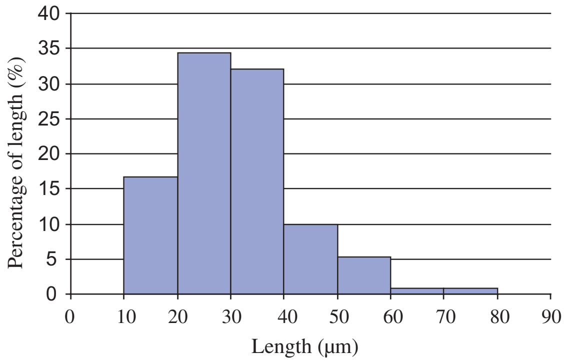

Fig. 2. Bar-distribution of whisker length in the 13th month storage in room ambient.

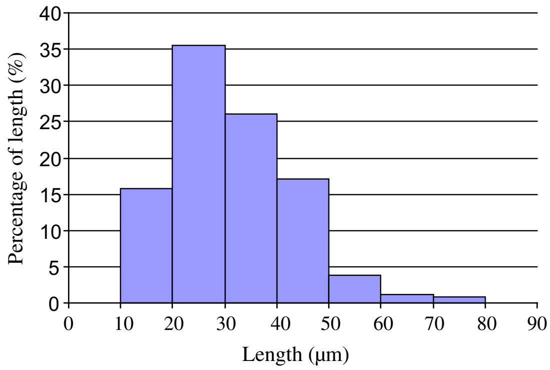

Fig. 3. Bar-distribution of whisker length in the 18th month storage in room ambient.

Individual whisker length is determined by the growth rate [12]. Several models on growth rate have been suggested, such as Furuta and Hamamura's model [13] and Tu's localized model [14]. Furuta and Hamamura modeled whisker growth rate as a function of vacancy formation energy, independent on tin-plating thickness. However, both the sample preparation process and the alloy utilized in the test were different from the industry techniques and processes which was the reason that this model was not adopted. Tu proposed a model, whereby the weak or cracked spots in the Sn oxide layer were considered as the dominant element for growth rate. Whisker growth rate was strongly affected by IMC, but no direct evidences were found to support this model.

Table 3
Summary of whisker length distribution fitting

Storage duration (month)	Mean (μm)	Standard deviation (μm)	Fitting goodness	Average increase rate of mean (μm/month)
8	24.0	12.7	0.9997	3.00
13	25.7	11.5	0.9976	0.34
18	26.0	11.4	0.9967	0.06

5. Discussion and summary

The summary of distribution fitting for tin whisker length is presented in Table 3. Based on the experimental results, the whisker density correlates with whisker-group length. This means that high whisker density has a large possibility to be coupled with large group-whisker-length. It also shows that the group-whisker length increases with time; but the rate is decreasing and approaches an equilibrium state. A model for this is

$$L_{\mathrm{m}}(t) = \mathrm{A} * (1 - e^{-\mathrm{B}*t}),$$

where L_{m} is the mean of the group-whisker length in microns, t is the storage duration in hours, and A and B are constants. In our study, A is 28.0 and B is 2.78×10^{-4}.

In summary, the lognormal distribution was found to offer the best fit to whisker length for the observed period for the case of tin plated over brass with the exposures of annealing followed by temperature/humidity. The group-whisker growth rate distribution is the same as group-whisker length distribution with different coefficients. Based on the experimental results, the whisker density is found to correlate with whisker length. Accordingly, special attention should be paid to high whisker densities. Finally, probabilistic methods offer a good way to model whisker growth and assess the effectiveness of tin whisker risk mitigation strategies.

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